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Annual Evaluation of Availability of Hydrologically Connected Water Supplies

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Table of Contents

Table of Figures	v
Table of Tables	vii
I. Summary	I-1
II. Introduction	
Purpose	I-1
Background	I-3
Report Organization	I-8
III. Legal Requirements	
Section 46-713(1)(a) – Annual Evaluation and Report Required	L-1
Section 46-713(1)(b) – Preliminary Conclusions following Basin Evaluations	L-2
Section 46-713(3) – Determination that a Basin is Fully Appropriated	L-3
IV. Methodologies	
Overview	M-1
Lag Impacts	M-7
Surface Water Appropriations	M-8
Specific Calculations	M-9
Existing and Projected Ground Water Well Development	M-9
Hydrologically Connected Area	M-12
Data Preparation	M-13
Principal Aquifer and Hydraulic Connection	M-14
SDF Calculations	M-14
10/50 Management Area Analysis	M-16
Converting Inches of Net Corn Crop Irrigation Requirement to Days Necessary to Divert	M-17
Future Impact of Current Ground Water Well Development and of Additional Ground Water Well Development	M-18
Study Area Boudaries	M-19
Depletive Wells	M-19
Future Well Development	M-20
Annual Depletions Calculations	M-20
Development of Ground Water Irrigated Acres per Well	M-23
Method 1: Average Method	M-23
Method 2: 1995 Study Ground Water Irrigated Acres	M-23
Method 3: Combination of 1995 Report Results and 2002 Agriculture Census Data	M-24
Determination of Erosion	M-29
Bibliography	M-31

V. Basins

Blue River Basins
Summary B-1
Basin Descriptions B-1
Nature and Extent of Water Use B-4
Ground Water B-4
Surface Water B-6
Hydrologically Connected Area B-8
Big Blue River Basin B-8
Little Blue River Basin B-10
Net Corn Crop Irrigation Requirement B-12
Surface Water Closing Records B-14
Long Term Surface Water Supply Evaluation B-15
Future Water Supply B-15
Depletions Analysis B-16
Irrigation Surface Water Appropriation Analysis B-17
Ground Water Recharge Sufficiency B-18
Sufficiency to Avoid Noncompliance B-19
Future Development B-20
Future Analysis B-22
Conclusions B-22
Bibliography B-23

Lower Niobrara River Basin
Summary N-1
Basin Description N-1
Nature and Extent of Water Use N-3
Ground Water N-3
Surface Water N-5
Hydrologically Connected Area N-7
Net Corn Crop Irrigation Requirement N-9
Surface Water Closing Records N-11
Long-Term Surface Water Supply Evaluation N-11
Future Water Supply N-11
Depletions Analysis N-12
Irrigation Surface Water Appropriations Analysis N-13
Instream Flow Surface Water Appropriation Analysis N-13
Ground Water Recharge Sufficiency N-14
Sufficiency to Avoid Noncompliance N-14
Future Development N-15
Future Analysis N-17
Conclusions N-17
Bibliography N-18

Lower Platte River Basin
Summary P-1

Basin Description P-1
Subbasin Relationships P-4
Nature and Extent of Water Use P-7
Ground Water P-7
Surface Water P-10
Hydrologically Connected Area P-12
Net Corn Crop Irrigation Requirement P-14
Surface Water Closing Records P-16
Long-Term Surface Water Supply Evaluation P-17
Future Water Supply P-17
Depletions Analysis P-19
Irrigation Surface Water Appropriation Analysis P-20
Instream Flow Surface Water Appropriation Analysis P-23
Ground Water Recharge Sufficiency P-26
Sufficiency to Avoid Noncompliance with Other State and Federal Laws P-26
Future Development P-26
Future Analysis P-32
Conclusions P-33
Bibliography P-34

Missouri Tributary Basins
Summary MT-1
Basin Descriptions MT-1
Nature and Extent of Water Use MT-4
Ground Water MT-4
Surface Water MT-6
Hydrologically Connected Area MT-8
Net Corn Crop Irrigation Requirement MT-10
Surface Water Closing Records MT-12
Long-Term Surface Water Supply Evaluation MT-12
Future Water Supply MT-12
Depletions Analysis MT-13
Irrigation Surface Water Appropriation Analysis MT-14
Ground Water Recharge Sufficiency MT-14
Sufficiency to Avoid Noncompliance MT-15
Future Development MT-15
Future Analysis MT-16
Conclusions MT-16
Bibliography MT-18

VI. Basin Summaries and Results
Basin Summaries
Blue River Basins BS-1
Lower Niobrara River Basin BS-2
Lower Platte River Basin BS-3
Missouri Tributaries Basins BS-4

Results of Analyses BS-5

Appendices

Appendix A – Public Notice for Additional Information
Appendix B – Nebraska Administrative Code Title 457 Chapter 24
Appendix C – Basic Assumptions Used in the Development of the Department of Natural Resources Proposed Method to Determine Whether a Stream and the Hydrologically Connected Ground Water Aquifers are Fully Appropriated
Appendix D – Net Irrigation Requirement
Appendix E – A Groundwater Model to Determine the Area within the Upper Big Blue Natural Resources District where Groundwater Pumping has the Potential to Increase Flow from the Platte River to the Underlying Aquifer by at Least 10 Percent of the Volume Pumped over a 50-Year Period
Appendix F – Computation of Rate and Volume of Stream Depletion by Wells
Appendix G – USGS Review Letter

Table of Figures

Figure I-1. Areas Hydrologically Connected to Fully and Overappropriated Basins, Subbasins, and Reaches I-7
Figure M-1. Net Corn Crop Irrigation Requirement M-3
Figure B-1. General Basin Map, Blue River Basins B-3
Figure B-2. Current Well Development by Number of Registered Wells, Blue River Basins B-4
Figure B-3. Current Well Locations, Blue River Basins B-5
Figure B-4. Surface Water Appropriations by Number of Diversion Points, Blue River Basins B-6
Figure B-5. Surface Water Appropriation Diversion Locations, Blue River Basins B-7
Figure B-6. Areas of Ground Water and Surface Water Connection, Upper Big Blue NRD B-9
Figure B-7. 10/50 Area, Little Blue River Basin B-11
Figure B-8. Net Corn Crop Irrigation Requirement, Blue River Basins B-13
Figure B-9. Annual Precipitation, Blue River Basins B-16
Figure B-10. High Capacity Well Development, Blue River Basins B-21
Figure N-1. General Basin Map, Lower Niobrara River Basin N-2
Figure N-2. Current Well Development by Number of Registered Wells, Lower Niobrara River Basin N-3
Figure N-3. Current Well Locations, Lower Niobrara River Basin N-4
Figure N-4. Surface Water Appropriations by Number of Diversion Points, Lower Niobrara River Basin N-5
Figure N-5. Surface Water Appropriation Diversion Locations, Lower Niobrara River Basin N-6
Figure N-6. 10/50 Area, Lower Niobrara River Basin N-8
Figure N-7. Net Corn Crop Irrigation Requirement, Lower Niobrara River Basin N-10
Figure N-8. Annual Precipitation, Lower Niobrara River Basin N-12
Figure N-9. High Capacity Well Development, Lower Niobrara River Basin N-16
Figure P-1. General Basin Map, Lower Platte River Basin P-3
Figure P-2. Map of Subbasin of the Platte River Basin above the North Bend Gage P-6
Figure P-3 Current Well Development by Number of Registered Wells, Lower Platte River Basin P-8
Figure P-4. Current Well Locations, Lower Platte River Basin P-9
Figure P-5. Surface Water Appropriations by Number of Diversion Points, Lower Platte River Basin P-10
Figure P-6. Surface Water Appropriation Diversion Locations, Lower Platte River Basin P-11
Figure P-7. 10/50 Area, Lower Platte River Basin P-13
Figure P-8. Net Corn Crop Irrigation Requirement, Lower Platte River Basin P-15
Figure P-9. Annual Precipitation, Lower Platte River Basin P-18
Figure P-10. Mean Annual Flow, Platte River near Duncan P-19
Figure P-11. High Capacity Well Development, Lower Platte River Basin P-28

Figure MT-1. General Basin Map, Missouri Tributary Basins MT-3
Figure MT-2. Current Well Development by Registered Number of Wells, Missouri Tributary Basins MT-4
Figure MT-3. Current Well Locations, Missouri Tributary Basins MT-5
Figure MT-4. Surface Water Appropriations by Number of Diversion Points, Missouri Tributary Basins MT-6
Figure MT-5. Surface Water Appropriation Diversion Locations, Missouri Tributary Basins MT-7
Figure MT-6. 10/50 Area, Missouri Tributary Basins MT-9
Figure MT-7. Net Corn Crop Irrigation Requirement, Missouri Tributary Basins MT-11
Figure MT-8. Annual Precipitation, Missouri Tributary Basins MT-13
Figure MT-9. High Capacity Well Development, Missouri Tributary Basins MT-16

Table of Tables

Table M-1. Number of Ground Water Irrigated Acres per Well M-26
Table M-2. Number of Irrigation Wells by Basin M-27
Table M-3. Number of Non-Irrigation Wells by Use by Basin M-28
Table B-1. Surface Water Administration in the Big Blue River Basin, 1986-2005 B-14
Table B-2. Surface Water Administration in the Little Blue River Basin, 1986-2005 B-14
Table B-3. Comparison between the Number of Days Required to Meet the Net Corn Crop Irrigation Requirement and Number of Days Surface Water is Available for Diversion in the Big Blue River Basin. B-18
Table B-4. Comparison between the Number of Days Required to Meet the Net Corn Crop Irrigation Requirement and Number of Days Surface Water is Available for Diversion in the Little Blue River Basin B-18
Table B-5. State Line Flow Targets for the Big Blue River B-20
Table N-1. Surface Water Administration in the Lower Niobrara River Basin, 1986-2005 N-11
Table N-2. Comparison between the Number of Days Required to Meet the Net Corn Crop Irrigation Requirement and Number of Days Surface Water is Available for Diversion in the Lower Niobrara River Basin N-13
Table N-3. Long Pine Creek Instream Flow Appropriation Evaluation N-14
Table P-1. Surface Water Administration in the Lower Platte River Basin above the North Bend Gage, 1986-2005 P-16
Table P-2. Surface Water Administration in the Lower Platte River Basin above the Louisville Gage, 1986-2005 P-16
Table P-3. Estimate of Days Available for Diversion above North Bend P-21
Table P-4. Estimate of Days Available for Diversion above Louisville P-22
Table P-5. Comparison between the Number of Days Required to Meet the Net Corn Crop Irrigation Requirement and Number of Days Surface Water is Available for Diversion at North Bend P-23
Table P-6. Comparison between the Number of Days Required to Meet the Net Corn Crop Irrigation Requirement andNumber of Days Surface Water is Available for Diversion at Louisville P-23
Table P-7. Number of Days North Bend Instream Flow Appropriation Expected to be Met P-25
Table P-8. Number of Days Louisville Instream Flow Appropriation Expected to be Met P-25
Table P-9. Estimated Number of Days Surface Water is Available for Diversion above North Bend with Future Development . P-30
Table P-10. Estimated Number of Days Surface Water is Available for Diversion above Louisville with Future Development. P-31
Table P-11. Comparison between the Number of Days Required to Meet the Net Corn Crop Irrigation Requirement and Number of Days Surface Water is Available for Diversion above North Bend with Future Development. P-32
Table P-12. Comparison between the Number of Days Required to Meet the Net Corn Crop Irrigation Requirement and Number of Days Surface Water is Available for Diversion above Louisville with Future Development. P-32

Table MT-1. Surface Water Administration in the Missouri Tributary Basins, 1986-2005 MT-12
Table MT-2. Comparison between the Number of Days Required to Meet the Net Corn Crop Irrigation Requirement and Number of Days Surface Water is Available for Diversion in the Missouri Tributary Basins MT-14
Table BS-1. Summary of Comparison between the Number of Days Required to Meet 65% of the Net Corn Crop Irrigation Requirement and Number of Days in which Surface Water is Available for Diversion (July1 – August 31). BS-6
Table BS-2. Summary of Comparison between the Number of Days Required to Meet 85% of the Net Corn Crop Irrigation Requirement and Number of Days in which Surface Water is Available for Diversion (May 1 – September 30). BS-7

I. SUMMARY

The Department of Natural Resources (Department) has evaluated the expected long-term availability of surface water supplies and hydrologically connected ground water supplies of the Blue River basins, the Lower Niobrara River Basin, the Lower Platte River Basin, and the Missouri Tributaries basins, and has concluded that none of the basins or any of the subbasins or reaches within the basins are fully appropriated at the present time. In only one subbasin, the subbasin of the Platte River above the North Bend gage, did the analysis of the long-term water supply with no additional constraints on ground water and surface water development conclude that the determination would change to being fully appropriated based on reasonable projections of the extent and location of future development in the subbasin.

II. INTRODUCTION

Purpose

The purpose of this report is to fulfill the requirements of section 46-713 of the Ground Water Management and Protection Act (Act) (Neb. Rev. Stat. §§ 46-701 through 46-753). The Act requires the Department to annually report its evaluation of the expected long-term availability of hydrologically connected water supplies. This annual evaluation is required on every river basin, subbasin, or reach that has not either initiated the development of an integrated management plan (IMP) or implemented an IMP. No reevaluations were made in 2006 for basins, subbasins, or reaches that have IMPs, or for which IMPs are being prepared.

This year the Department's report has grouped its evaluation and preliminary conclusions regarding the sufficiency of surface water and hydrologically connected ground water supplies into four river basins: the Blue River basins, the Lower Niobrara River Basin, the Lower Platte River Basin, and the Missouri Tributaries basins. This was done to reduce repetition, however, the analysis was still applied on each appropriate subbasin and reach. As required by law, the report also describes the nature and extent of present water uses in the basin, the geographic area considered to have hydrologically connected surface and ground water supplies, and how the Department's preliminary conclusions might change if there are no new legal restrictions on water development in the basin. The report does not address the sufficiency of ground water supplies that are not hydrologically connected to surface water streams. The report includes a description of the criteria and methodologies used to determine which basins, subbasins, or reaches are preliminarily considered to be fully appropriated and which water supplies are hydrologically connected. The report is required to include a summary of relevant data provided by any interested party concerning the social, economic, and environmental impacts of additional hydrologically connected surface water and ground water on resources that are dependent on streamflow or ground water levels but are not protected by appropriations or regulations, however, no data were provided to the Department for this report. Appendix A contains the notice of the request for any relevant data from any interested party.

Background

This report is intended to address requirements that were added to the Act by passage of LB 962 in 2004. That bill was in turn influenced by actions taken as a result of prior legislative activity. In 2002, the Nebraska Unicameral passed LB 1003, mandating creation of a Water Policy Task Force to address conjunctive use management issues, inequities between surface water and ground water users, and water transfers/water banking. The 49 Task Force members appointed by the Governor from a statutorily specified mix of organizations and interests were asked to discuss issues, identify options for resolution of issues, and make recommendations to the legislature and Governor relating to any water policy changes deemed desirable.

In December 2003, the Task Force provided the legislature with the *"Report of the Nebraska Water Policy Task Force to the 2003 Nebraska Legislature."* That report provided draft legislation and suggested changes to statutes. The legislature considered the Task Force recommendations in its 2004 session and subsequently passed LB 962, which incorporated most of the Task Force recommendations. Governor Mike Johanns signed the bill into law on April 15, 2004.

The provisions of LB 962 require a proactive approach in anticipating and preventing conflicts between surface water and ground water users. Where conflicts already exist it establishes principles and timelines for resolving those conflicts. It also adds more flexibility to statutes governing transfer of surface water rights to a different location of use and updates a number of individual water management statutes.

Some of the key provisions of LB 962 that are part of current statutes include:

- Provisions for action if basins are determined to be fully appropriated or declared overappropriated. A basin will be determined to be fully appropriated when, considering current and potential future development, the balance between surface water and ground water cannot be sustained. An overappropriated basin is one where the extent of development is not sustainable over the long run. The law also automatically placed natural resources districts undertaking an integrated management process under previous law for integrated management of hydrologically connected ground water and surface water into fully appropriated status.

- Beginning by January 1, 2006, the Department must make an annual determination of which basins, subbasins, or reaches not previously designated as fully appropriated or overappropriated have since become fully appropriated. The Department must also complete an annual evaluation of the expected long-term availability of hydrologically connected water supplies in the basins, subbasins, or reaches and issue a report describing the results of the evaluation.

- When a basin, subbasin, or reach is declared overappropriated or determined to be fully appropriated, stays on new uses of ground water and surface water shall be imposed. The Department and the natural resources districts (NRDs) involved are required to jointly develop and implement an integrated management plan within 3 to 5 years of that designation.

- A key goal of each IMP will be to manage all hydrologically connected ground water and surface water for the purpose of sustaining a balance between water uses and water supplies so that the economic viability, social and environmental health, safety, and welfare of the basin, subbasin, or reach can be achieved and maintained for both the near and long term.

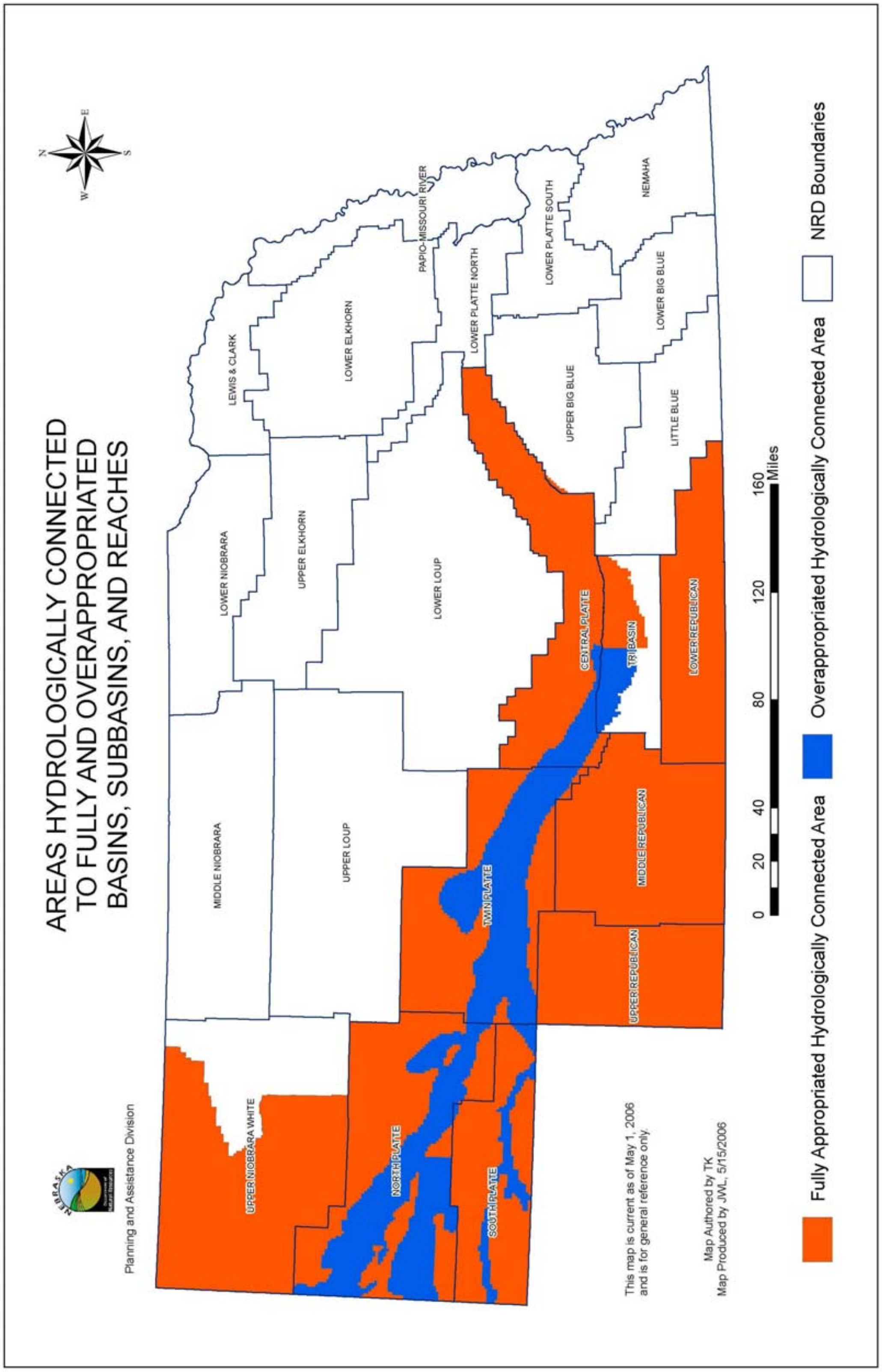
- IMPs may rely on a number of voluntary and regulatory controls including incentives, allocation of ground water withdrawals, rotation of use, and reduction of irrigated acres among others.

- If there are disputes between the Department and the NRDs over the development or implementation of an IMP that cannot be resolved, the Governor will appoint a five member Interrelated Water Review Board to resolve the issue.

- Specific provisions for transfers of surface water rights, adjudication of surface water rights, and transfer of ground water off the overlying land as well as certain other provisions were incorporated into the bill.

Subsequent to passage of LB 962, a number of basins, subbasins, or reaches have been designated as fully or overappropriated (Figure I-1). The report on the first statutorily required evaluation of hydrologically connected water supplies was issued on December 30, 2005, and is entitled *"2006 Annual Evaluation of Availability of Hydrologically Connected Water Supplies."* Compact discs of that report are available from the Department upon request. This volume is a report on the second statutorily required annual evaluation.

Figure I-1. Areas Hydrologically Connected to Fully and Overappropriated Basins, Subbasins, and Reaches



Report Organization

This report is divided into seven sections. Section I is the report summary. Section II is the introduction to the report and contains the purpose, background, and organization. The pertinent statutory and regulatory language can be found in Section III and in Appendix B of this report. Detailed descriptions of the methodologies used in the analyses can be found in Section IV. Section V is the evaluations of the Big Blue River basins, the Lower Niobrara River Basin, the Lower Platte River Basin, and the Missouri Tributaries basins. Each basin evaluation includes a description of the nature and extent of present water uses, the geographic area considered to have hydrologically connected ground and surface water (10/50 area), preliminary conclusions about the adequacy of the long term water supply, and whether the preliminary conclusions would change if there are no additional constraints placed on water development in the basin. Section VI is a summary of the basin subsections and the report conclusions. The appendices contain additional detailed information not found within the main body of the report.

III. LEGAL REQUIREMENTS

Section 46-713(1)(a) – Annual Evaluation and Report Required

A river basin's hydrologically connected water supplies include the surface water in the watershed or catchment that runs off to the stream and the ground water that is in hydrologic connection with the stream. For all evaluated basins, the geographic areas of hydrologically connected surface water and ground water, if any, are shown on a basin-wide map that is included with each basin subsection. In those maps, the surface watershed basin is shown by a solid line and the ground water portion of the basin is depicted by a shaded area.

Surface water supplies are considered to be hydrologically connected to a stream or stream reach if the surface water is draining to the streams. In accordance with Department rule 457 N.A.C. 24.001.02, the Department considers the area within which ground water is hydrologically connected to a stream to be that area within which "pumping of a well for 50 years will deplete the river or a base flow tributary thereof by at least 10% of the amount pumped in that time." For purposes of the evaluation and the report, a river basin may be divided into two or more subbasins or reaches. Only those basins that have not initiated development or implemented an IMP are required to be evaluated.

In preparing its annual report, the Department is required by section 46-713(1)(d) to rely on the best scientific data, information, and methodologies readily available to ensure that the conclusions and results contained in the report are reliable. A list of the information the Department uses can be found in rule 457 N.A.C. 24.002 (Appendix B). The Department is also required to provide enough documentation in the report to allow others to independently replicate and assess the Department's data, information, methodologies, and conclusions. That documentation can be found throughout the report. The raw data used for these calculations and the spreadsheets with the calculations are provided on the attached compact disc.

Section 46-713(1)(b) – Preliminary Conclusions following Basin Evaluations

As a result of its annual evaluation, the Department is to arrive at a preliminary conclusion as to whether or not each river basin, subbasin, and reach evaluated is currently fully appropriated without the initiation of additional uses. The Department is also required to determine if and how its preliminary conclusions would change if no additional legal constraints were imposed on future development of hydrologically connected surface water and ground water. This determination is based on reasonable projections of the extent and location of future development in a basin.

Section 46-713(3) – Determination that a Basin is Fully Appropriated

The Department must make a final determination that a basin, subbasin, or reach is fully appropriated if the current uses of hydrologically connected surface and ground water in the basin, subbasin, or reach cause, or will in the reasonably foreseeable future cause, either (a) the surface water supply to be insufficient to sustain over the long term the beneficial or useful purposes for which existing natural-flow or storage appropriations were granted, (b) the stream flow to be insufficient to sustain over the long term the beneficial uses from wells constructed in aquifers dependent on recharge from the river or stream involved, or (c) reduction in the flow of a river or stream sufficient to cause noncompliance by Nebraska with an interstate compact or decree, other formal state contract or agreement, or applicable state or federal laws. Since these factors must be considered in making the final determination, they must also be part of the Department's considerations in reaching its preliminary conclusions.

The Department considered whether or not condition (c) would be met with regard to interstate compacts by reviewing the terms of any compacts in each basin and determining when noncompliance would occur if there were sufficient reductions in streamflow. There were no decrees, formal state contracts or agreements in any of the basins evaluated this year; there is one interstate compact covering the Blue River basins.

With regard to noncompliance with state and federal law, it was determined that only the state and federal laws prohibiting the taking of threatened and endangered species could raise compliance issues that would trigger condition (c). The federal Endangered Species Act, 16 U.S.C. §§1530 *et. seq.* prohibits the taking of any federally listed threatened or endangered species of animal by the actual killing or harming of an individual member of the species (16 U.S.C. §1532) and also by degrading or destroying a species' habitat so much that the species cannot survive (50 CFR §17.3). The state Nongame and Endangered Species Conservation Act, Neb. Rev. Stat. §§37-801 *et. seq.* also prohibits the actual killing or harming of an individual member of a listed species, but it is not clear whether the degradation of the species' habitat is considered a taking under state law. The Department reviewed information from the Nebraska Game and Parks Commission about the possible existence of species listed as threatened and endangered in the river basins that the Department evaluated, whether those species actually lived in the rivers or streams and, for those species living in the streams evaluated, whether those species' habitat requirements included an identified level of streamflow. The Department reached a preliminary conclusion that reductions in flow will not cause noncompliance with either federal or state law at this time in any of the basins evaluated.

Prior to making a final determination that a basin, subbasin, or reach is fully appropriated, the Department must also hold a public hearing on its preliminary conclusions and consider any testimony and information given at the public hearing or hearings.

IV. METHODOLOGIES

Overview

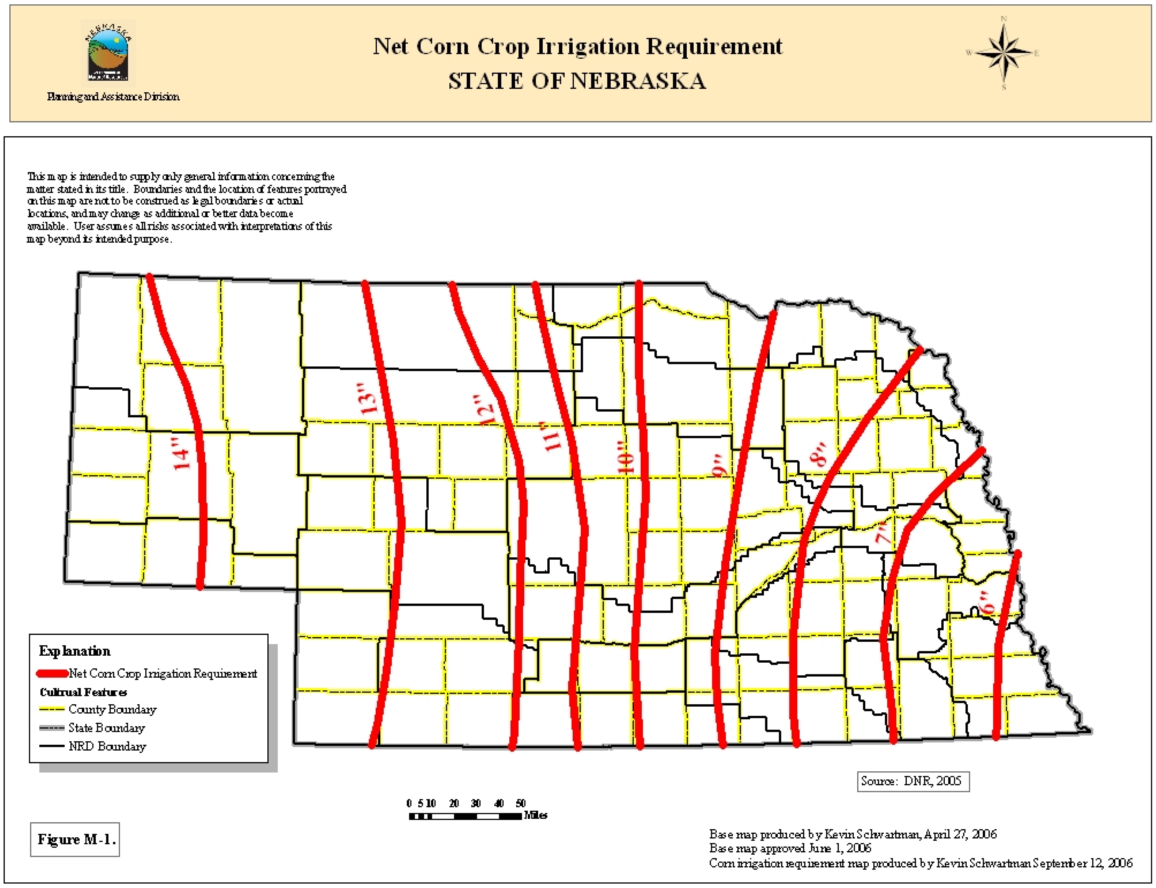
To make its preliminary conclusions, the Department followed the criteria in 46-713(2) using regulation 457 N.A.C. 24.001 (Appendix B). The Department assessed how its preliminary conclusions might change by predicting future water uses based on the rate of water use development in the past. These predictions take into account the presence of existing wells and location of lands unsuitable for irrigation ("reasonable projections"). Existing legal restraints on water development such as well drilling moratoriums established by natural resources districts were also factored into the predictions.

The methodology chosen was to meet the requirement of Section 46-713(3) which generally states that a basin is fully appropriated if current uses of hydrologically connected surface water and ground water in a basin cause or will cause in the reasonably foreseeable future (a) the surface water to be insufficient to sustain over the long term the beneficial purposes for which the existing surface water appropriations were granted or (b) the streamflow to be insufficient to sustain over the long term the beneficial uses from wells constructed in aquifers dependent on recharge from the basin's river or stream. For reasons explained in Appendix C, if condition (a) was met, condition (b) would also be met.

In general terms, regulation 457 N.A.C. 24 states that the surface water supply is deemed to be insufficient if, at current levels of development, over the last twenty years the most junior irrigation right in a basin, subbasin, or reach is unable to divert sufficient surface water to provide 85% of the amount of water a corn crop needs (the Net Corn Crop Irrigation Requirement) during the irrigation season (May 1 through September 30) or if the most junior irrigation right in a basin, subbasin, or reach is unable to divert 65% of the amount of water a corn crop needs during the key growing period of July 1 through August 31.

The rule focuses on the irrigation of corn because the most frequent beneficial use of water in all of the basins evaluated is for corn. The net corn crop irrigation requirements for each basin are set out in each basin subsection. The requirements are based on the average evapotranspiration of corn that is fully watered to achieve the maximum yield and the average amount of precipitation that is effective in meeting the net corn crop irrigation requirements for the area. Figure M-1 shows the net corn crop irrigation requirements for the state. The development of net corn crop irrigation requirements is described in Appendix D.

Figure M-1 Net Corn Crop Irrigation Requirement



If there is sufficient water for the most junior irrigation appropriation, all irrigation appropriations will be satisfied. Therefore, the Department analyzed the water available to the most junior appropriator. When making the calculation of the number of days surface water was available to the most junior irrigation surface water appropriator, the Department assumed that if the appropriator was not closed, he or she could have diverted at the full permitted diversion rate. The historical record was adjusted to include the impacts of all currently existing surface water appropriations and the projected future impacts from currently existing ground water wells, i.e. the lag effect. The lag effect was determined using the number of water wells located in the hydrologically connected area that will impact the water supply over the next 25-year period. Details on how the lag effect was calculated can be found later in this section.

If the 65%/85% criteria are not met the final step in a preliminary conclusion of whether a basin is fully appropriated is to apply what has been termed “the erosion rule” (457 N.A.C. 24.001.01C). This rule takes into account the fact that appropriations may be granted even though there isn’t enough water available at the time they are granted to divert enough water to satisfy the 65% and 85% optimal diversion days requirement. So, if the Department’s calculations revealed that the most junior surface water appropriator could not meet the 65% or 85% tests, the Department used historic streamflow data to calculate the average number of days the most junior surface water appropriator would have been able to divert given the priority date of the appropriation. If, at the time of the priority date of the most junior appropriation, the surface water appropriation could not have diverted surface water a sufficient number of days on average for the previous 20 years to satisfy the 65% and 85% diversion requirements, the surface water supply for the basin is deemed insufficient only if the average number of days surface water could have been diverted over the previous 20 years is less than the average number of days surface water could have been diverted for the 20 years previous to the time of the priority date of the appropriation. In other words, a basin is determined to be fully appropriated only if the appropriation right has actually been eroded over the last twenty years. When making these calculations, the Department takes into account the lag effect of wells existing at the time of priority date.

According to regulation 457 N.A.C.24.001.01B, in the event that the junior water rights are not irrigation rights, the Department will utilize a standard of interference appropriate for the use, to determine whether flows are sufficient for the use, taking into account the purpose for which the appropriation was granted.

In the Lower Platte Basin and the Lower Niobrara Basin, there are junior non-irrigation instream flow rights. To determine if water use development has interfered with the ability of these water rights to obtain water for their instream flow purposes the Department used the erosion rule. The purpose of the instream flow permits is to maintain, not enhance, habitat for the fish community existing at the time of the priority date on the permit. Therefore, the Department determined that an appropriate standard of interference would be to determine if the instream flow requirements that could be met at the time the water rights were granted can still be met today. To apply the erosion rule, the Department calculated the average number of days the instream flow could have been expected to be met in the 20 years previous to the time of the appropriation date on the permit. This was done by determining the number of days the instream flow requirements could have been met using the streamflow data from the 20 years just prior to the date of the appropriation, and considering the lag effects from wells existing at the date of the appropriation, and then comparing these results to the number of days the instream flow requirements are met under current development, considering lag effects from currently existing wells. The two calculations were compared on a month by month basis.

Regulation 457 N.A.C. 24.001.02 states that the geographic area within which the ground and surface water are hydrologically connected is determined by calculating where, in each river basin, a well would deplete a river's flow by 10% of the amount of water the well could pump over a 50 year period (the 10/50 area). These calculations are not dependent on the quantity of water pumped but are dependent on each basin's geologic characteristics and the distance between the well and the stream. When there was a valid hydrogeologic numerical model available to determine the 10/50 area, it was used. When there was not a valid numeric model available, the stream depletion factor methodology was used (Jenkins, 1968) (Appendix F).

The methodologies used for determining the hydrologically connected ground water area (10/50 area) of a basin are described in detail later in this section. When making the decision of which methodology is appropriate to use for this purpose in each basin, an evaluation of the existing information and the ability to utilize that information in an acceptable manner directed the selection. The method used and the reasoning for using that method is described for each basin in each basin subsection. Each of the methodologies used in our evaluation has a documented history of being used extensively for this type of analysis for water management purposes.

A numerical ground water model (MODFLOW) developed by the Upper Big Blue Natural Resources District using Cooperative Hydrology Study (COHYST) data was reviewed by the Department and deemed suitable for delineating the extent of the area hydrologically connected (10/50 area) to the Little Blue River (Appendix E).

Unfortunately, in many areas of the state there are no sufficient numerical ground water models, such as MODFLOW, available, nor are the data required to develop such a model available. Until such time as these data and models can be developed, the Department must rely on less data-intensive analytical models such as the Glover-Balmer or Jenkins methods, Appendix F. The use of the Jenkins method for this report was peer reviewed by the United States Geological Survey, Appendix G. The Jenkins method was used in the Lower Niobrara River Basin, the Lower Platte River Basin, and the Missouri Tributaries basins.

There are areas of the state, such as the Big Blue River Basin, where information regarding hydrologic conditions are so inadequate that it is not possible to use any method currently available to determine the 10/50 area or the lag impact of ground water pumping.
The data used in the above methodologies and throughout the report comes from published reports from the University of Nebraska-Conservation and Survey Division, and represents the most current publication available. These data include information on transmissivity, specific yield, saturated thickness, depth to water, surficial geology, bedrock geology, water table elevation change, water table elevation, characteristics of aquifers and test-hole information. These data are available on the UNL-Conservation and Survey Division website: http://csd.unl.edu/. Additional data used in the report comes from the U.S. Geological Survey through their website which is located at http://waterdata.usgs.gov/ne/nwis/gw and represents the most current publication available. The data actually used in the report is available on the attached compact disc.

Lag Impacts

For purposes of this report, lag impacts are defined as the delayed effect that the consumptive use of water associated with well pumping will have on hydrologically connected streamflow and the associated impact on surface water appropriations. In accordance with Department rule 457 N.A.C. 24.001.01, when making the determination of future water supplies, the Department must also take into account the lag impacts of ground water uses on water supplies over the next 25 years. The calculation of the lag impacts for the next 25 years from current well development was evaluated by analyzing the impact from high capacity wells, that is wells pumping greater than 50 gallons per minute, that were part of the registered well database as of December 31, 2005. Expected future ground water uses, including their lag impacts, were also calculated to determine their impact on the water supply over the next 25 years. In some basins, the lag impact was not calculated due to a lack of appropriate data or models. In those cases, because the number of days in which surface water is available for diversion so far exceeded the number of days necessary to meet the net corn crop irrigation requirement, the final conclusion would most likely not change even with the addition of lag impacts.

Specific information about the methodologies used can be found in the individual basin subsections or later in this section.

Surface Water Appropriations

Surface water appropriations in Nebraska are administered under the doctrine of prior appropriation. The basis for the doctrine is “first in time, first in right.” When there is a surface water shortage, the surface water appropriation that has a senior priority date has the right to use any available water, up to its permitted value, before any upstream junior surface water appropriation can use water. To exercise a senior right, the senior water appropriation will put a call on the stream, and the Department will investigate the streamflows and, if necessary, issue closing orders to the upstream junior water appropriations, starting with those with the most junior priority dates. Although additional surface water development in a basin will deplete the overall surface water supplies during times when there is excess surface water, under the priority system a junior right can not cause a senior surface water appropriation supply to be reduced. Therefore, in areas where surface water administration is already occurring, additional surface water development in the basins will not reduce the number of days surface water is available for diversion by a senior surface water appropriation. In areas that have not experienced surface water administration, it is not feasible to predict that point at which additional surface water development may cause surface water administration to occur.

Specific Calculations

Based on regulation 457 N.A.C. 24, for this report, the Department considered 25 years in the future to be "long term." "Water supply" includes precipitation and ground water discharge, which occurs as baseflow, and streamflow from tributaries. All surface water appropriations as of December 31, 2005, were considered to be "existing surface water uses."

Existing and Projected Ground Water Well Development

The Department's Water Well Registration database was used to determine "existing ground water uses." In order to make the report as up to date as possible, it was necessary to estimate the number of all wells registered in 2006 because wells are not registered simultaneously with their completion. "New ground water uses" were determined by projecting all future water well registrations based on the current rate of water well registrations for all types of wells in each basin, taking into account known limitations, such as moratoriums, on future well development. Not all wells in existence are registered in the Department database, especially livestock and domestic wells, which if drilled prior to 1993 are not required to be registered. Certain dewatering and other temporary wells are also not required to be registered.

Limitations of hydrologic modeling and method must be considered by the user of the model and method when considering the results and analyses, and the appropriateness of such for the given task. Historically three broad categories of models have been used to study ground water flow systems, i.e. sand tank models, analog models, and mathematical models, including analytical methods and numerical models. The first two methods were primarily used prior to the advent of the modern high speed digital computers. Since the advent of computers, numerical models have been the favored type of model for studying ground water.

One widely used numerical model that was developed by the U.S. Geological Survey is MODFLOW (McDonald and Harbaugh 1988). A previous study compared the results of several analytical methods to a two-dimensional ground water flow model with wells located in close proximity to the stream (312.5 feet) pumped for a short period of time (58 days). The study showed that for the given parameters used in the simulation, the simplifying assumptions needed for use of the analytical methods resulted an overestimation in stream flow depletion from the numerical model that ranged from 20 percent, due to neglect of partial penetration, to 45 percent, due to neglect of clogging layer resistance (Spaulding and Khaleel 1991).

However, when looking at a regional impact and a longer time period, such errors are much less acute. This is because the dominant factor in determining the impact of a pumping well on a stream is the distance of the well from the stream. Thus, the impact of any other differences in actual hydrologic and geologic conditions and the idealized assumptions used in the Jenkins method decrease as the distance from the stream and any relevant boundary conditions increase. For this reason, these differences are minimal when analyzing impacts on a regional scale (pers. com. with Luckey 2006). Fox (2004) also concludes it is reasonable to use simplified analytical solutions for long term water management.

For those areas of the state where an existing MODFLOW model suitable for regional analysis is available, it is used to develop the 10/50 areas. However, much of the state is not covered by suitable numerical models and in some areas the data necessary to develop a model are also lacking. In order to properly use a numerical model a substantial amount of quality-assured data must be supplied as inputs to the numerical model. In these areas an analytical method described by Jenkins in 1968 was used.

Although clearly not as precise as a numerical model, the analytical Jenkins method, commonly known as the Stream Depletion Factor (SDF) (Jenkins 1968) (Appendix F), lends itself to the basin-wide aspect of the task described by this report. The method Jenkins described was based on simplifying assumptions (Jenkins 1968) and was built upon equations previously published by Glover and Balmer (1954), Maasland and Bittinger (1963), Gautuschi (1964), and others. The Jenkins method has been used by other states, including Colorado and Wyoming, for water administrative purposes.

Modified versions of the Jenkins SDF method were also considered because the assumptions in the original Jenkins method do not always fit real world situations. Jenkins SDF can be modified to address situations such as boundary conditions (Miller and Durnford 2005) and streambed conductance (Zlotnik 2004). The modifications require data on these parameters to perform the analysis. No modifications were made to Jenkins for this analysis because of the lack of published data necessary for the calculations. Generally these additional calculations are required only when wells are near the stream or boundary condition. As one moves away from the stream the percent impact of the parameters becomes a small fraction of the overall total. This concept is supported by comments from Dick Luckey (USGS 2005).

Hydrologically Connected Area

In the area covered by a numerical model the steps taken to define the 10/50 line and associated hydrologically connected area are documented in Appendix E. The upper portion of the Little Blue River was evaluated by a numeric ground water model derived from the COHYST model to do the analysis and draw the 10/50 line. In areas that are not covered by an acceptable numerical model but where sufficient data existed, the following steps were taken to define the 10/50 area using SDF Methodology:

1. Data preparation (data can be found in attached CD).
    - Develop transmissivity maps and associated datasets for all basins being studied.

- Develop specific yield maps and associated datasets for all basins being studied.
- Select appropriate maps of perennial stream reaches.
- Use Geographic Information System (GIS) software to develop point grids and associated SDF values.

2. Evaluate available data to determine if the principal aquifer is present and if sufficient data exist to determine that a given stream reach is in hydraulic connection with the principal aquifer.

3. Complete SDF calculations using customized GIS software.

4. Modify the point shapefile to create the 10/50 management area.

Data Preparation

The following data were necessary for determining the 10/50 area.

- Aquifer transmissivity and specific yield
- Locations of perennial streams
- Grid of points within study area

The aquifer properties used in the study were found in the report “Mapping of Aquifer Properties – Transmissivity and Specific Yield – for Selected River Basins in Central and Eastern Nebraska” published by the Conservation and Survey Division (CSD 2005).

The location and extent of perennial streams were found from the permanent streams GIS coverage available from the Conservation and Survey Division. The main stems of each river and its tributaries were included in the calculations for individual basins.

A grid of points was created in ArcView GIS. These points were spaced at one-mile intervals within and beyond the study area. ArcView is a GIS program used to view, process, and query spatially referenced data.

Principal Aquifer and Hydraulic Connection

This information was primarily determined from maps generated by the Conservation and Survey Division (CSD 2005). Other supporting evidence from published reports was also used in some cases and is referenced where used.

SDF Calculations

There are two terms necessary to make the 10/50 area determination at each point in the grid, the depletion percentage term and the SDF term.

Depletion percentage: v/Qt

Dimensionless term: $\frac{tT}{a^2 S}$

Where: v = volume of stream depletion during time t

Qt = net volume pumped during time t

t = time during the pumping period since pumping began

T = average transmissivity of the aquifer between the well and the stream

a = perpendicular distance between the well and stream

S = average specific yield of the aquifer between the well and the stream

A large number of calculations are necessary to make the 10/50 area determination. To facilitate this effort, ArcView was customized to do much of the work. The goal of the process was, for each grid point, to determine the above aquifer properties and then to solve the above equations for the distance term, ‘a’, and compare that value to the actual distance from the point to the perennial stream. The known values for the equations are:

- t is 50 years or 18262 days.
- T is the aquifer transmissivity – which is determined by computing the average of each transmissivity cell along the perpendicular line between the well and the perennial stream in ArcView.
- S is the aquifer specific yield – which is determined by computing the average of each specific yield cell along the perpendicular line between the well and the perennial stream in ArcView.

- v/Qt is equal to 10% or 0.1. From the nomograph (Appendix F) relating the depletion percentage and the dimensionless term, the corresponding dimensionless term value is equal to 0.359.

Once the value for the distance term ‘a’ is solved for each point, it can be compared to the actual computed perpendicular distance of the 10/50 boundary to the perennial stream. If the distance for each point is less than the computed perpendicular distance of the 10/50 boundary, the point is included as part of the 10/50 area. All points that met this requirement were stored as a point shape file for further analysis.

The 10/50 analysis was only completed for points that fell in areas where the principle aquifer exists and is in hydraulic connection with the stream. These areas were defined from information found in the CSD aquifer properties report (CSD 2005).

10/50 Management Area Analysis

To define the location of the 10/50 boundary, the point shape file created in the analysis above was converted to a grid using ArcView functions. The process of converting the point shapefile into a polygon grid shapefile resulted in a series of one-mile by one-mile grid cells centered on the points in the point shapefile. All of the grid cells were then merged into a single polygon. The resulting polygon had ‘jagged’ edges which were removed to produce a polygon with a ‘smoothed’ appearance. After smoothing, some of the 10/50 areas extended into areas previously defined by the CSD as consisting of no principle aquifer or having no hydraulic connection with the stream. The smoothed polygon was modified to remove such areas.

The final 10/50 area polygon was then converted into a 10/50 management area polygon by determining the portion of each section of land that fell within the 10/50 area polygon. If 50% or more of the section polygon fell within the 10/50 area polygon, the section was included. The final edit to the 10/50 management area polygons was to clip out the sections of land in the areas that fell outside of the perennial streams that formed the boundaries to the study areas.

Converting Inches of Net Corn Crop Irrigation Requirement to Days Necessary to Divert

Assumptions include a downtime of 10%, due to mechanical failures and other causes, a diversion rate of 1 cubic foot per second (cfs) per 70 acres, as this is the most common rate approved by DNR for surface water appropriations, and an irrigation efficiency of 80%. Steps include:

- Interpolate between the Net Corn Crop Irrigation Requirement contours using the spline methodology in ArcView 3.x to get Net Corn Crop Irrigation Requirement.
- Multiplying the Net Corn Crop Irrigation Requirement by 0.65 or 0.85 to find the 65% and 85% inches.
- Converting 1 cfs/70 acres to inches per day
    - 1 cfs = 1.983 acre-feet/day
    - 1 foot = 12 inches

- (1 / 70) * 1.983 * 12 = 0.34 inches / day

- Calculate the Gross Irrigation Requirement by dividing the 65% and 85% values by 0.8 (the irrigation efficiency)
- Calculate the number of days for which deliveries must be made for both the 65% and 85% criteria by dividing the gross irrigation requirement for each value by the 0.34 inches per days rate of diversion, and by 0.9 to account for the downtime
  - Number of days = $\frac{\text{Gross Requirement}}{(0.34)(0.9)}$

Future Impact of Current Ground Water Well Development and of Additional Ground Water Well Development

Similar to the analysis of the hydrologically connected area, the analysis of ground water well development can also be computed using SDF equations and nomographs. Two separate analyses were performed: 1) determine the lag impacts of the well development that has occurred as of December 31, 2005, and estimated well development for 2006 twenty-five years into the future, and 2) determine the lag impacts of current plus continued well development twenty-five years into the future.

The following steps were taken to compute the lag impact for each of the two analyses:

1. Define the study area.
2. Determine which wells result in a consumptive use of water that will deplete streamflows (high capacity depletive wells).
3. Project the locations of wells that will be part of the future development in the basin. These wells were only considered for the second analysis of future well development.

4. Calculate the annual volume of depletion the stream will experience due to the existing wells and future wells for the next 25 years at five-year increments using SDF methodology.
5. Convert annual acre-feet values to average annual cubic feet per second values to estimate streamflow impact.

Study Area Boundaries

The study area surface water boundary for each river basin is defined by the watershed boundary. The study area ground water boundary is defined by certain features that include the location of perennial baseflow streams, location of non-hydrologically connected areas, ground water table highs that prevent flow to the stream of interest, and where there is a ground water model available to determine the 10/50 area.

Depletive Wells

Not every well in the Department well database was used to calculate lag impacts. Only high capacity (rate of pumping greater than 50 gpm) active irrigation, industrial, public water supply, or unprotected public water supply wells (public water supply wells without statutory spacing protection) were selected for this analysis. Other depletive wells such as abandoned or inactive high capacity wells, livestock watering wells, and domestic wells were not included because of the relatively small amount of water they use and because the database is not complete for these types of wells.

Future Well Development

The rate of future development was estimated by projecting the linear trend of the current rate of high capacity well development over the last 10 years into the future. The future wells were located geographically within the study area by randomly placing each future well on U.S. Department of Agriculture defined irrigable soils. To ensure that land was available for development, a 1,400 foot radius circle (slightly larger than the radius of an average center pivot) was drawn around every existing well, and all lands already irrigated within the circles were removed from the inventory of irrigable land that has not been irrigated. In addition, all irrigable land areas available for new development of less than 40 acres in size were excluded.

Annual Depletions Calculations

In order to estimate the future stream depletions, the level of depletion for five year increments was calculated for 2016, 2021, 2026, and 2031. A depletion value was calculated for each existing depletive well in the study area using SDF methodology. The terms used in this methodology include the depletion percentage term and the dimensionless term.

Depletion percentage: v/Qt

Dimensionless term: $\frac{tT}{a^2S}$

The goal of the depletion analysis is to solve for the ‘v’ term, the cumulative volume of stream depletion at the end of each five year period. The rest of the variables in the equation are known and have previously been described.

Q is the annual volume of water pumped for consumptive use over the age of the well in acre-feet. This is calculated by multiplying the net corn crop irrigation requirement by an average field size in acres. The average field size was estimated to be 90 acres (DNR 2005). The average field size was developed using the results described in the “Development of Ground Water Irrigated Acres per Well” subsection of this section. Industrial and public water supply wells are treated the same as irrigation wells for this analysis.

Each high capacity depletive well in the basin has this type of analysis completed and entered into the database. The depletion values in the database are modified for wells that fall within multiple basin study areas. If the well falls into two basin study areas, the depletion is divided by 2, if it falls within three basin study areas, the depletion is divided by 3. This type of modification is done so that the total depletion is not overestimated in overlapping areas. This is an appropriate adjustment because if there are a sufficient number of wells in an overlapping area between two basins, they will likely, on average, be halfway between the two basins. Since SDF methodology is distance based, splitting the depletion in half and assigning half of the total depletion to each basin is a reasonable way to deal with the situation.

Once the process has been repeated for each five-year increment, the additional volume depleted from 2006 to year ‘X’ can be calculated by subtracting the cumulative depletion from 2006, the base year, from the cumulative depletion calculated for year ‘X’.

To estimate the lag impacts of current wells, the results from the twenty-five year depletion analysis can then be converted from annual acre-feet of depletion to an average annual cubic feet per second of water by dividing the difference between 2006 and the 2031 year value by 724.46 (the conversion factor for acre-feet/year to cfs). The depletion rate can then be used as the estimate of the daily reduction to streamflow over time.

To estimate the lag impacts of current wells and future well development, the results from the twenty-five year five-year increment depletion analysis can be converted from annual acre-feet of depletion to an average annual cubic feet per second of water by dividing the difference between 2006, the base year, and the five-year value by 724.46 (the conversion factor for acre-feet/year to cfs). The five-year average depletion rate can then be used as an estimate of the daily reduction to streamflow during the corresponding five-year increment.

Conversions from acre-feet per year to cubic feet per second:

- 1 cubic foot per second = 31,557,600 cubic feet per year
- 1 acre-foot = 43,560 cubic feet
- 1 cubic foot per second = 724.46 acre-feet per year

The methodology described in this subsection was independently peer reviewed by the Nebraska Water Science Center, U.S. Geological Survey in October of 2005. The conclusion was "The NWSC reviewers found the document technically sound." A copy of the peer review transmittal letter is in Appendix G.

Development of Ground Water Irrigated Acres per Well

Estimation of the number of acres irrigated per ground water well was determined by evaluating three methodologies:

Method 1: Average Method

All active irrigation wells in the Nebraska Department of Natural Resources Ground Water Well database were queried and geographically located within the nine study basins. The average registered acres per well was computed for each basin. The ground water well database acreage value was obtained from the applicant when the well is originally registered. An examination in the Republican River Basin showed that number was, on average, 25% to 33% higher than the actual measured number of irrigated acres. Therefore, three alternate variations for Method 1 have been produced, decreasing the acres per well by 25, 30, and 35%.

Method 2: 1995 Study Ground Water Irrigated Acres

Based on the number of ground water irrigated acres for each county in the U.S. Geological Survey / Nebraska Natural Resources Commission 1995 Water Use Study Report and the number of active irrigation wells for each county in 1995 from Nebraska Department of Natural Resources Ground Water Well database, the average number of acres per well for each county was computed. After attributing each irrigation well and its associated average number of irrigated acres into one of the nine study basins, the average irrigated acres per well for each basin was computed by dividing the total irrigated acres in the basin by the total number of irrigation wells in the basin.

Method 3: Combination of 1995 Report Results and 2002 Agriculture Census Data

The total number of irrigated acres and ground water irrigated acres by county in the 1995 Water Use Study Report, total irrigated acres by county from the 2002 U.S. Agriculture Census, and the number of active irrigation wells in 2002 from Nebraska Department of Natural Resources Well Database were used to estimate the number of irrigated acres per well in 2002.

By assuming that ground water acres accounted for 95% of the increase in irrigated acres between 1995 and 2002, ground water irrigated acres per county in 2002 were estimated as the 1995 ground water irrigated acres plus 95% of the change in irrigated acres between 2002 and 1995. Then, using the estimated ground water irrigated acres for each county in 2002 and the number of irrigation wells in 2002 from the DNR well database, an average number of acres per well for each county was computed.

All irrigation wells with their average acres per well by county were assigned to their corresponding basins using GIS analysis. Then the total number of acres and wells for each basin were totaled. An average number of acres per well by basin in 2002 was developed by dividing the total acres by the number of wells in each basin. The results obtained with the three methodologies are shown in Table M-1.

Table M-1. Number of Ground Water Irrigated Acres per Well.

Basin	Method 1				Method 2	Method 3
	Average	1A (75%)	1B (70%)	1C (65%)		
Big Blue	120	90	84	78	91.7	89.7
Elkhorn River	131	98.3	91.7	85.2	99.2	95.9
Little Blue	126	94.5	88.2	81.9	96.3	92.6
Loup River	126	94.5	88.2	81.9	85.6	80.7
Lower Platte	106	79.5	74.2	68.9	85.7	84.4
Missouri Tributaries					116.2	103.9
Nemaha	138	103.5	96.6	89.7	54.6	63.8
Niobrara	130	97.5	91	84.5	83.7	78.4
Tri-Basin					100.1	99.6

Examination of the results produced by the three methods indicates that the estimated acres are fairly similar. Method 1 was eliminated because selection of the correct percentage reduction for each basin would be purely an educated guess until such time as actual data is collected to substantiate the numbers. Method 2 produces defensible numbers but is limited by its use of 1995 data. Method 3 is the procedure with the best available data.

Method 3 was selected as the preferred alternative. This process utilizes the information from a very detailed study done in 1995, and calibrates it to actual survey data collected in the 2002 Census of Agriculture. This procedure offers the additional advantage that it can be re-calibrated when the 2007 Census of Agriculture becomes available to see how the average number of acres per well in each basin has changed over time. Between census years, the number of acres irrigated can be estimated using the current number of registered wells in each basin times the number of acres per well.

There are a total of 89,695 active irrigation wells in Nebraska as of October 2005. Registration information shows that 37,519 of these are not in the area included in the nine basins evaluated. A breakdown of the location of the remaining 52,176 irrigation wells is shown in Table M-2.

Table M-2. Number of Irrigation Wells by Basin.

Basin	Number of Irrigation Wells
Big Blue	14,169
Elkhorn River	8,350
Little Blue	6,720
Loup River	9,953
Lower Platte	5,375
Missouri Tributaries	1,642
Nemaha	411
Niobrara	4,030
Tri-Basin	1,526
Nine Basin Total	52,176

There are an additional 3,539 high capacity, non-irrigation wells registered in Nebraska. Of these, 1,220 are not in the nine basins evaluated. The remaining 2,319 wells are registered for a variety of uses: Aquaculture, Commercial/Industrial, Domestic, Livestock, Public Water Supplier, and Other. The distribution of these wells in the nine basins is shown in Table M-3.

Table M-3. Number of Non-Irrigation Wells by Use by Basin.

	Aquaculture	Commercial/ Industrial	Domestic	Livestock	Public Water Supply	Other	Total
Big Blue	4	58	19	12	244	12	349
Elkhorn River	2	88	18	79	230	31	448
Little Blue	1	21	15	9	114	10	170
Loup River	10	40	25	63	166	7	311
Lower Platte	3	108	51	8	292	29	491
Missouri Tributaries	5	72	18	20	137	14	266
Nemaha		16	2	1	135	4	158
Niobrara	3	3	5	17	72	4	104
Tri-Basin		11	2	1	8		22

The U.S. Environmental Protection Agency reports that consumptive use of water varies by use category (EPA, 2005). They estimated that the rate of water consumption is highest for livestock at 67%, followed by irrigation at 56%. Domestic use consumes 23%, while industrial/ mining and commercial uses consume 16% and 11% respectively. Thermoelectric use consumes only 3% while public uses and losses are not even quantified as consumptive use by the EPA.

Because these 2,319 wells are such a small portion of the total number of high capacity wells in the state (2%), and no data exists in the registration database to indicate the annual pumpage of these wells, no additional efforts were made to identify the pumpage and calculate consumptive use at this time.

Determination of Erosion

In cases where the 65%/85% criteria were not met, an additional test is done to determine if the right has been eroded from the time it was granted. The same test is also conducted for instream flow rights. The steps for determining whether the right has been eroded are as follows:

- The most recent daily streamflow records (1986-2005) are used as a base for the 20-year period to be analyzed.
- Determine the 25 year lagged ground water depletions from wells existing at the date the junior surface water appropriation was granted and subtract them from the daily streamflow record for the 20-years prior to granting the appropriation.
- Determine the 25 year lagged ground water depletions from wells existing at the current time and subtract them from the daily streamflow record for the previous 20-years (1986-2005).
- Assume that surface water administration would occur if the flow requirement of a senior surface water appropriation was greater than the depleted historical daily flow. It is possible that all junior surface water appropriations can be closed and there still will not be enough flow for the calling senior surface water appropriation. When the Department administers for a calling senior surface water appropriation, all upstream junior surface water appropriations, starting with the most junior appropriator, are shut off in order of priority no matter how far upstream, until the senior surface water appropriation right calling is satisfied.
- Conduct a month by month comparison of the average number of days available to the junior surface water appropriation to evaluate if the use has been eroded. If the days

available to the junior surface water appropriation during the current period (1986-2005) are less than the days available to the junior surface water appropriation for the 20-year period prior to granting the appropriation then the appropriation is deemed to be eroded.

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V. BASINS

Blue River Basins

Summary

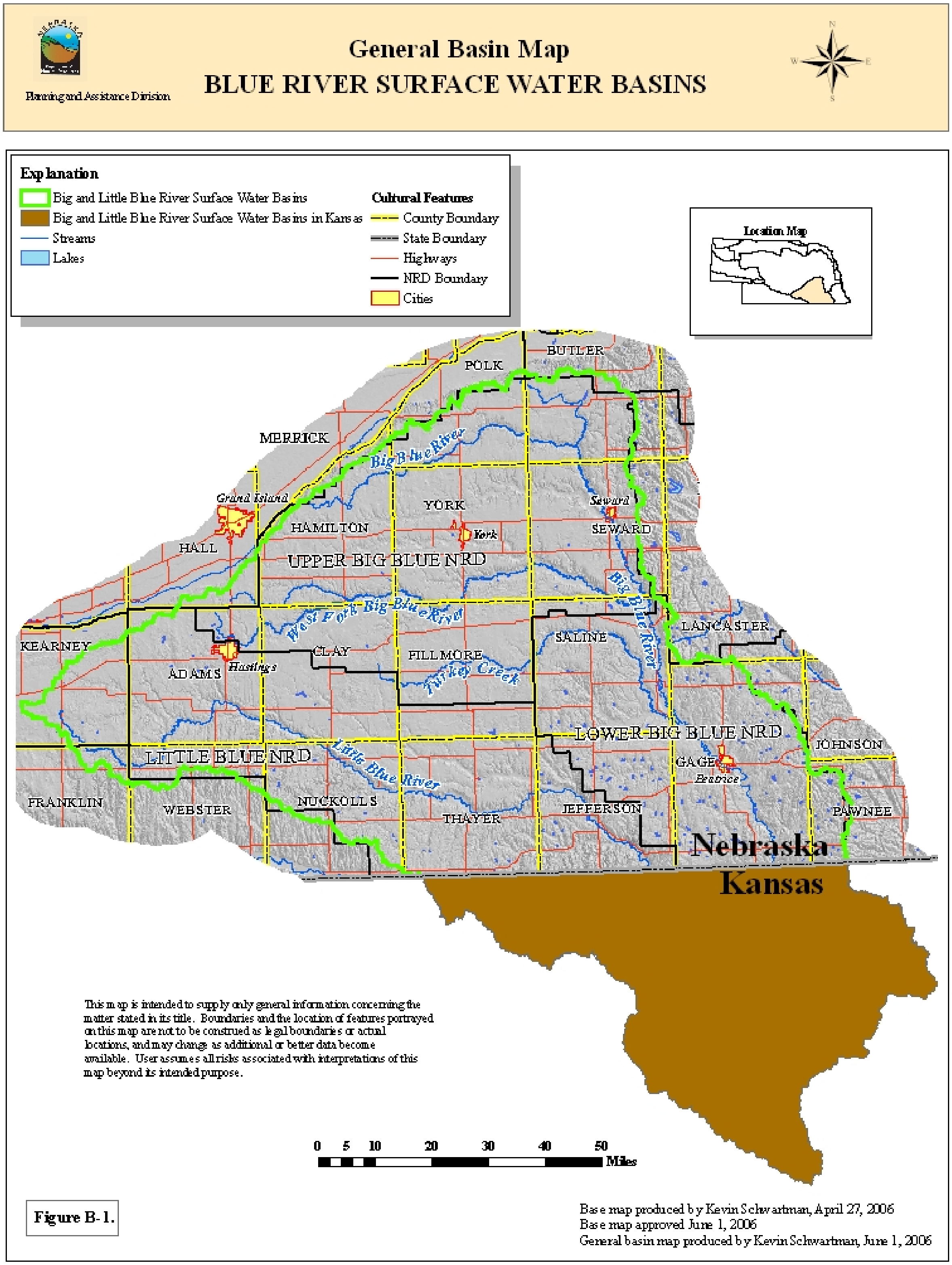
Based on the analysis of the sufficiency of the long-term surface water supply in the Blue River basins, the Department has reached a preliminary conclusion that the basins are not fully appropriated. Even though the effects on future water supplies were not estimated in the basins, the current number of days in which surface water was available for diversion far exceeds the number of days necessary to meet the net corn crop irrigation requirement. The best available data does not allow for analysis of whether or not this determination would change if no additional legal constraints are imposed on future development.

Basin Descriptions

The Blue River basins in Nebraska include all surface areas that drain into the Big Blue River and the Little Blue River, Figure B-1, and all areas of ground water which impact surface water flows of the basins. The total area of the Blue River surface water basins in Nebraska is approximately 7,100 square miles of which 4,600 square miles are in the Big Blue River Basin and 2,500 square miles are in the Little Blue River Basin. Natural Resources Districts with significant areas in the basins are the Little Blue Natural Resources District, the Lower Big Blue Natural Resources

District, the Upper Big Blue Natural Resources District, and the Tri-Basin Natural Resources District.

Figure B-1. General Basin Map, Blue River Basins.



Nature and Extent of Water Use

Ground Water

Ground water in the basins is used for a variety of purposes: domestic, industrial, livestock, irrigation, and other uses. There are a total of 24,546 registered ground water wells within the basins as of December 31, 2005 (Department registered ground water wells database), with an estimated 650 ground water wells to be developed during 2006, Figure B-2. The locations of all active ground water wells can be seen in Figure B-3.

Figure B-2. Current Well Development by Number of Registered Wells, Blue River Basins.

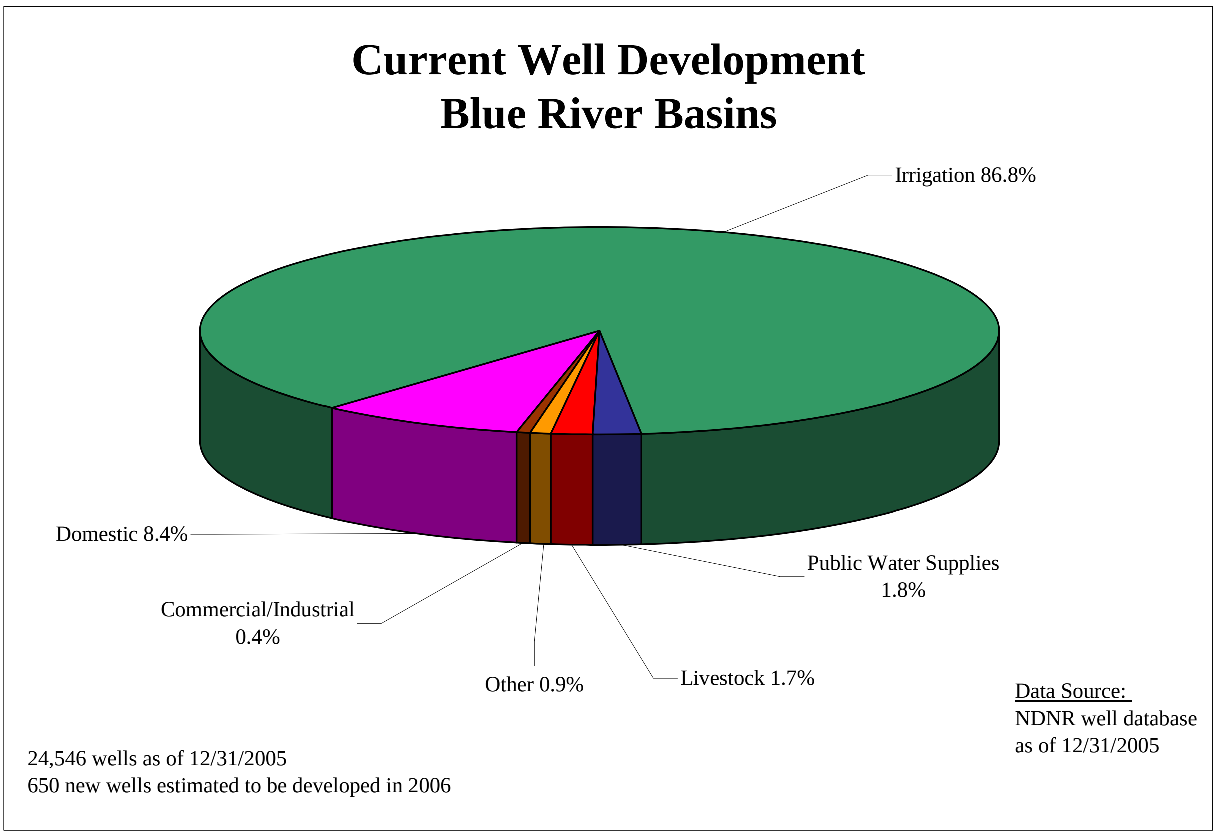
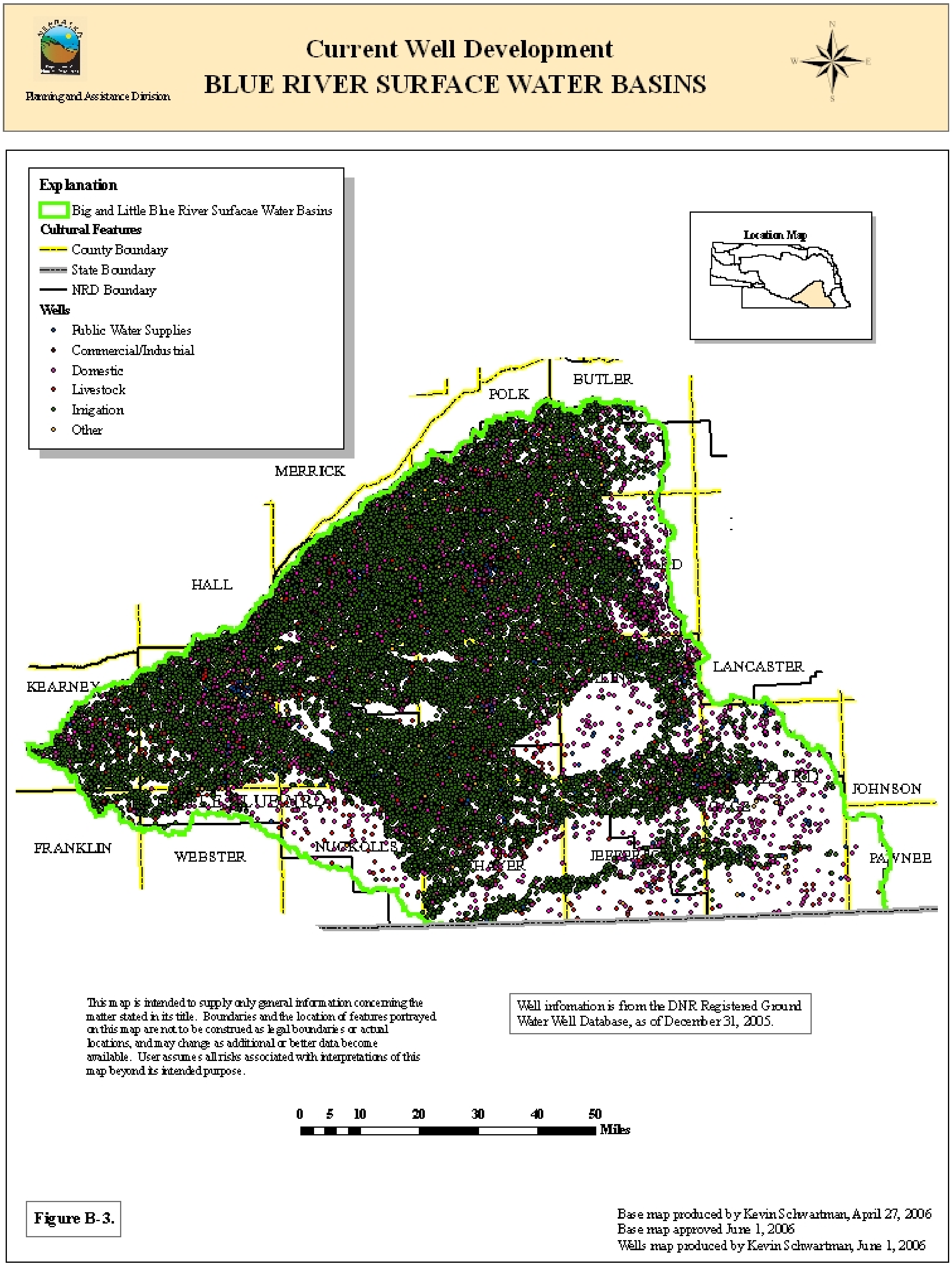


Figure B-3. Current Well Locations, Blue River Basins.



Surface Water

As of December 31, 2005, there were 2,397 surface water appropriations in the basins issued for a variety of uses, Figure B-4. The majority of the surface water appropriations are for irrigation and storage use and tend to be located on the major streams. The first surface water appropriations in the basins were permitted in 1868 and development has continued through present day. The approximate locations of the surface water diversions are shown in Figure B-5.

Figure B-4. Surface Water Appropriations by Number of Diversion Points, Blue River Basins.

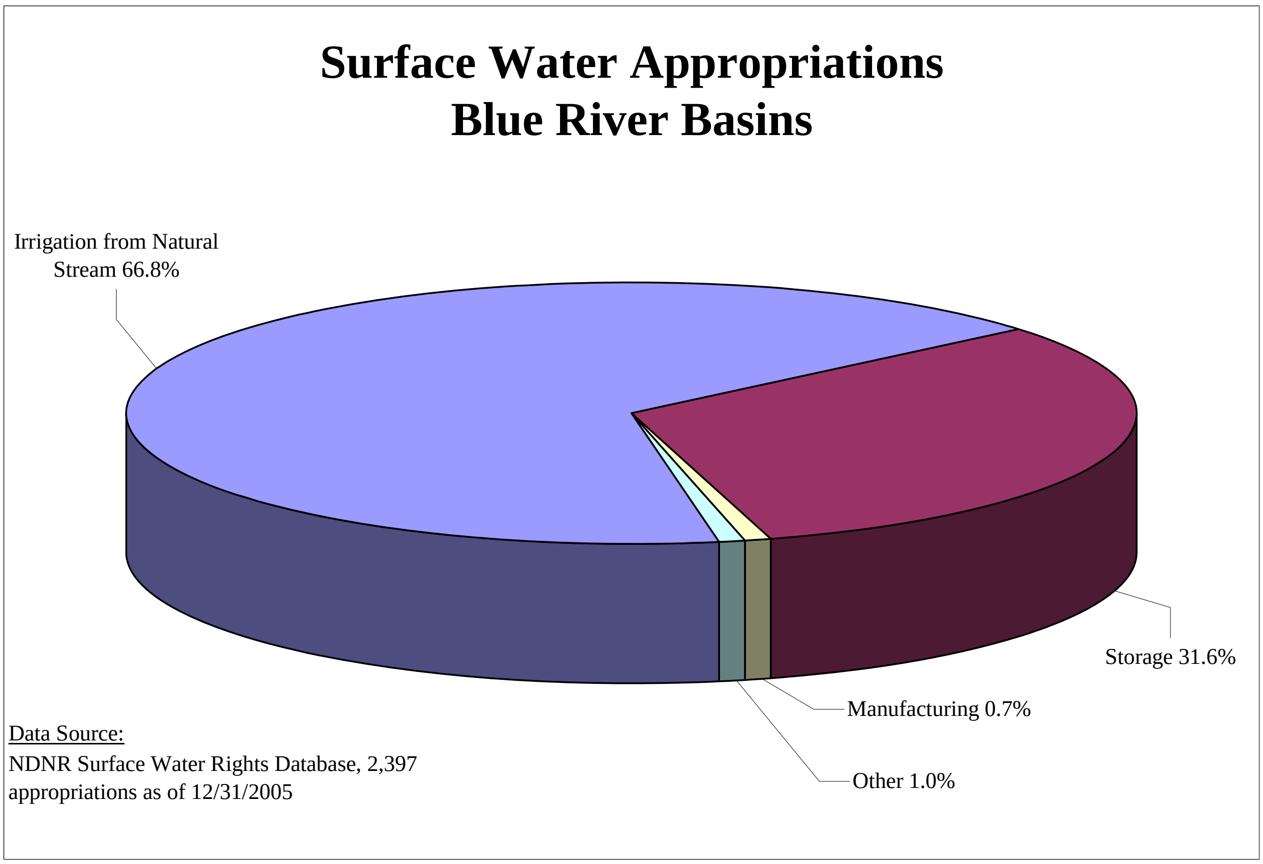
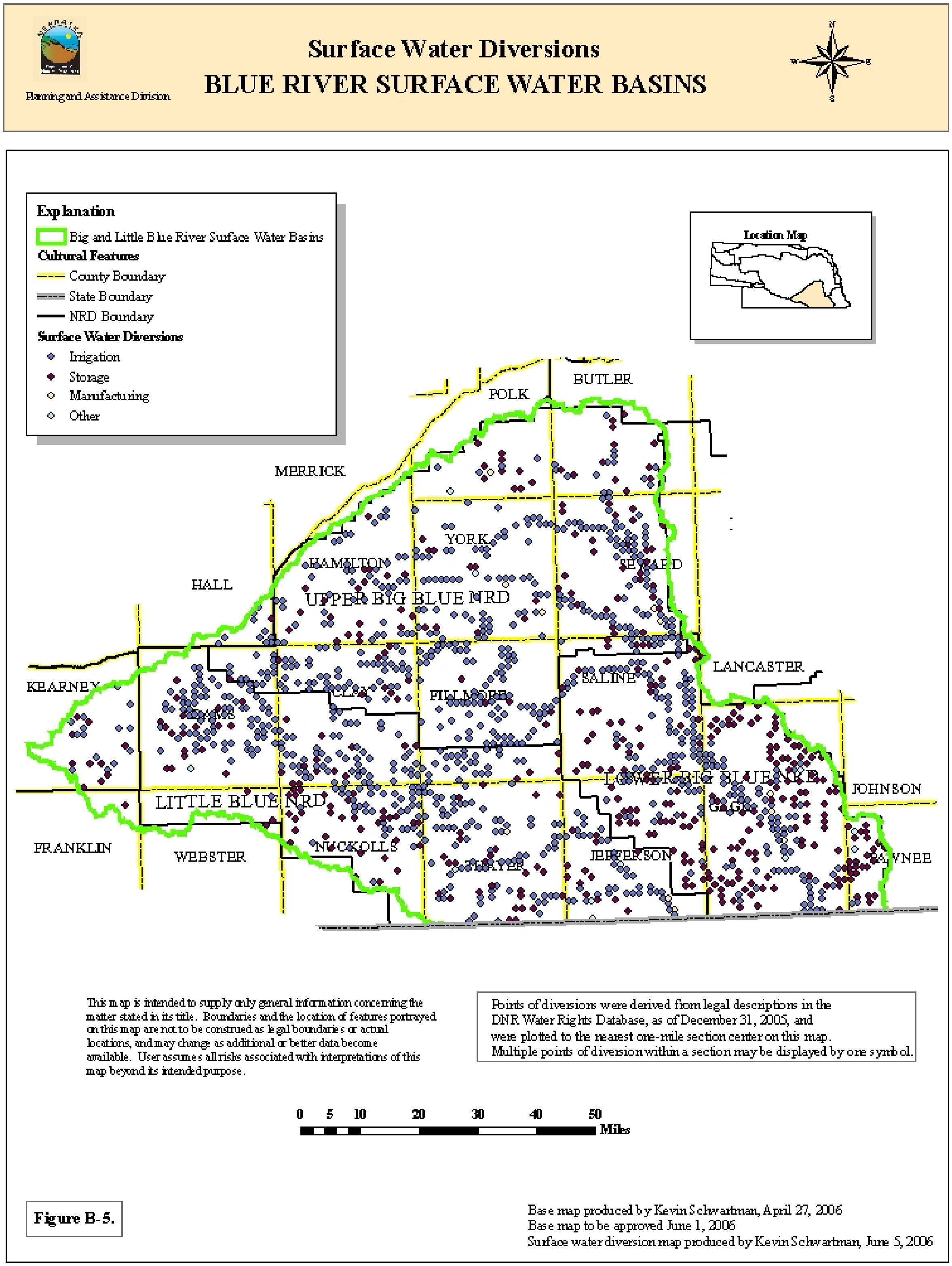


Figure B-5. Surface Water Appropriation Diversion Locations, Blue River Basins.



Hydrologically Connected Area

Big Blue River Basin

The Big Blue River Basin can be divided into two distinct areas based on whether or not it had been glaciated. In the glaciated areas the stream depletion factor (SDF) methodology cannot be used to delineate the 10 percent depletion in 50-year area (10/50 area) because the restrictive and complex nature of the hydrogeology of the glaciated portions of the basin violates the SDF methodology assumption that the aquifer consists of homogeneous, isotropic materials. At the present time the Department cannot determine the 10/50 area for the Big Blue River and its tributaries in these areas. The geology of the non-glaciated western area of the basin is less complex; however, in all but two small areas the principal aquifer is not in hydrologic connection with the streams because the water table is lower than the streambed elevation (Figure B-6) (Bitner, R. J. 2005).

Figure B-6. Areas of Ground Water and Surface Water Connection, Upper Big Blue NRD.

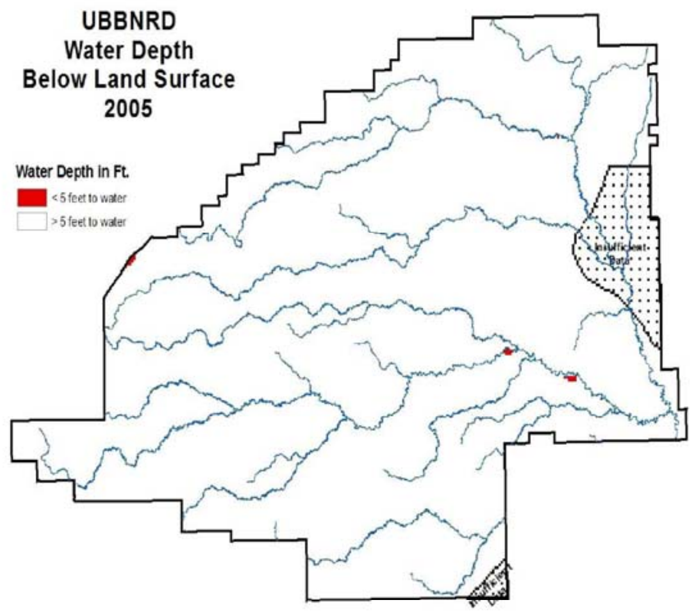


Figure B-6

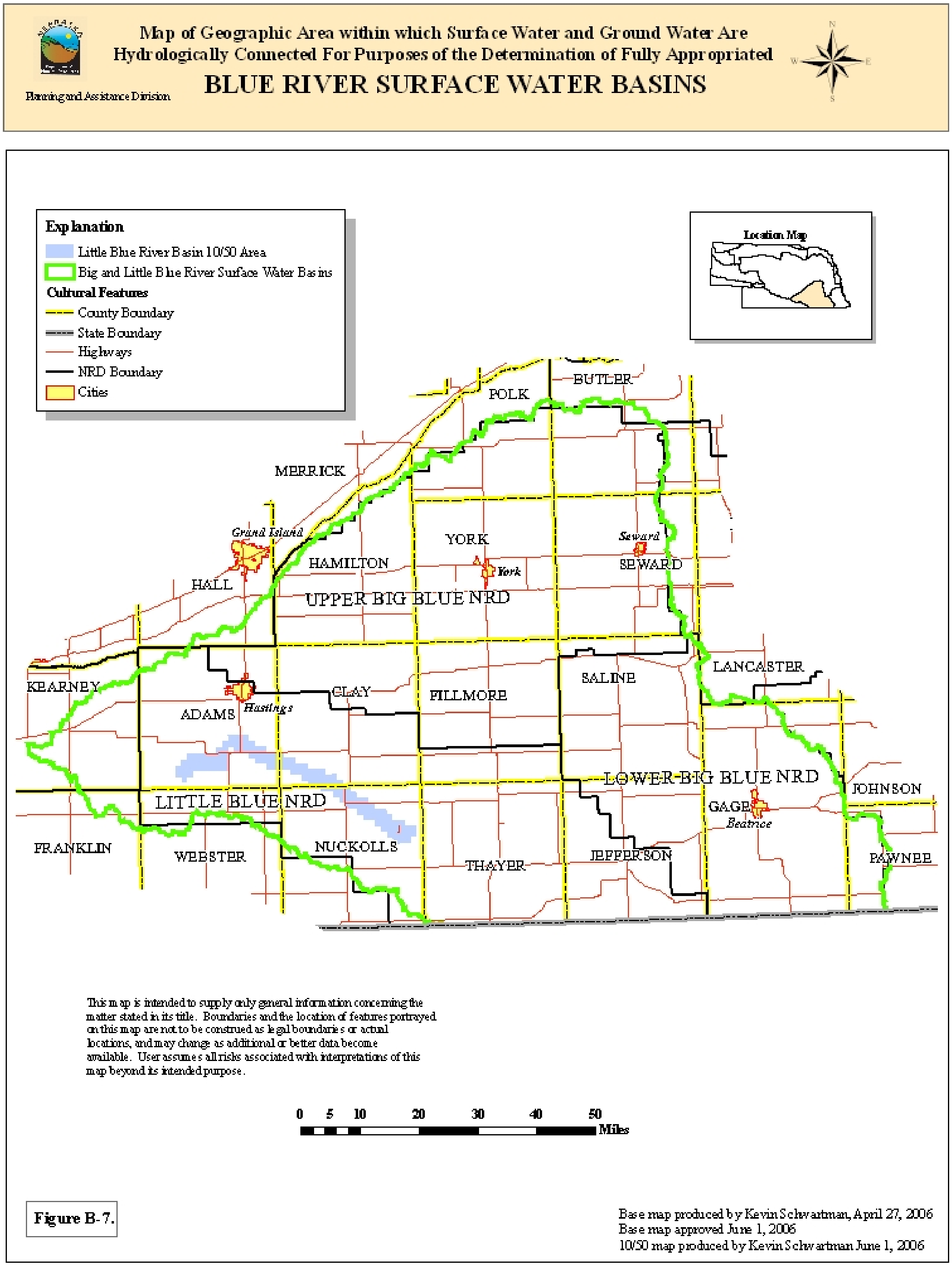
GENERAL DEPTH OF GROUNDWATER BELOW LAND SURFACE

Bitner, R.J., 2005

Little Blue River Basin

The Little Blue River Basin can also be divided into two distinct areas based on whether or not it had been glaciated. As with the Big Blue River Basin, the SDF methodology cannot be used to delineate 10/50 area because the restrictive and complex nature of the hydrogeology of the glaciated portions of the basin (CSD 2005) violates the SDF methodology assumption that the aquifer consists of homogeneous, isotropic materials. The 10/50 area for the other portions of the basin was determined from the results of the MODFLOW ground water model developed by the Upper Big Blue Natural Resources District (DNR 2005), Figure B-7.

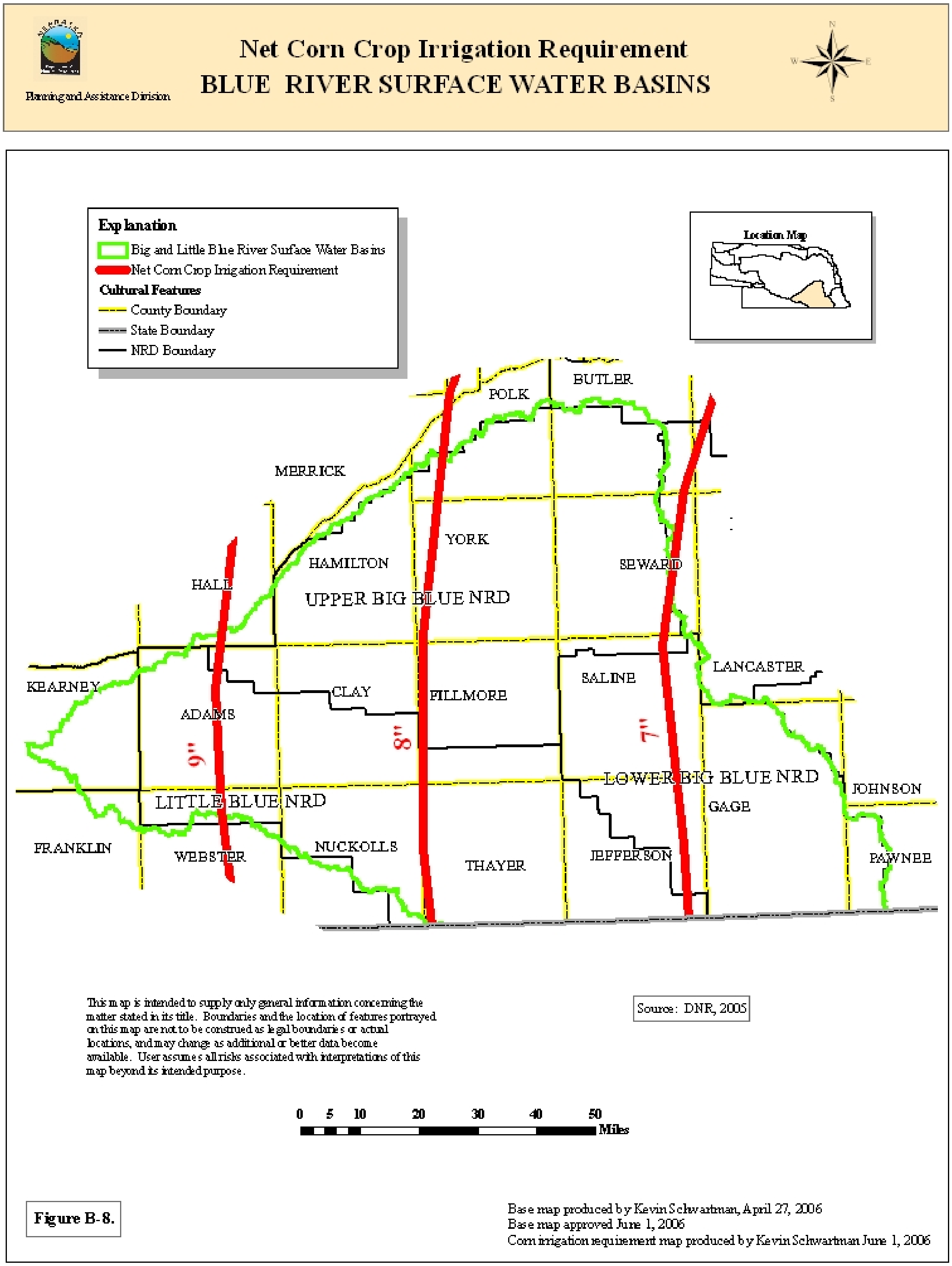
Figure B-7. 10/50 Area, Little Blue River Basin.



Net Corn Crop Irrigation Requirement

Figure B-8 is a map of the net corn crop irrigation requirement for the Blue River basins (DNR 2005). The greatest net corn crop irrigation requirement of a junior surface water appropriation in the Big Blue River Basin is 9.0 inches and the greatest net corn crop irrigation requirement of a junior surface water appropriation in the Little Blue River Basin is 9.7 inches. Assuming a surface water diversion rate equal to 1 cubic foot per second per 70 acres and a downtime value of 10 percent, it will take the junior surface water appropriation in the Big Blue River Basin 23.9 days annually to divert 65% of the net corn crop irrigation requirement and 31.3 days to divert 85% of the net corn crop irrigation requirement. For the junior surface water appropriation in the Little Blue River Basin, it will take 25.8 days annually to divert 65% of the net corn crop irrigation requirement and 33.7 days to divert 85% of the net corn crop irrigation requirement.

Figure B-8. Net Corn Crop Irrigation Requirement, Blue River Basins.



Surface Water Closing Records

Tables B-1 and B-2 record all surface water administration that has occurred in the basins between 1986 and 2005.

Table B-1. Surface Water Administration in the Big Blue River Basin, 1986-2005.

Year	Water Body	Days	Closing Date	Opening Date
2000	Turkey Creek	3	Jun 9	Jun 12
2000	Big Blue River above Lincoln Creek	2	Aug 15	Aug 17
2001	Big Blue River above Lincoln Creek	1	Aug 14	Aug 15
2002	Big Blue River above Lincoln Creek	11	Jul 11	Jul 22
2002	Big Blue River above Lincoln Creek	14	Jul 30	Aug 13
2002	Big Blue River Basin	8	Aug 5	Aug 13
2002	North Fork Big Blue River	1	Aug 14	Aug 15
2003	Big Blue River above Lincoln Creek	49	Jul 16	Sep 3
2003	Big Blue River Basin	11	Jul 17	Jul 28
2003	Big Blue River Basin	8	Aug 11	Aug 19
2004	Big Blue River above Lincoln Creek	16	Aug 3	Aug 19
2005	Big Blue River above Lincoln Creek	14	Jul 12	Jul 26
2005	Big Blue River Basin	13	Jul 13	Jul 26
2005	Big Blue River above West Fork	8	Jul 18	Jul 26
2005	Big Blue River above Lincoln Creek	11	Aug 4	Aug 15
2005	Big Blue River Basin	6	Aug 9	Aug 15
2005	Big Blue River above West Fork	5	Aug 10	Aug 15

Table B-2. Surface Water Administration in the Little Blue River Basin, 1986-2005.

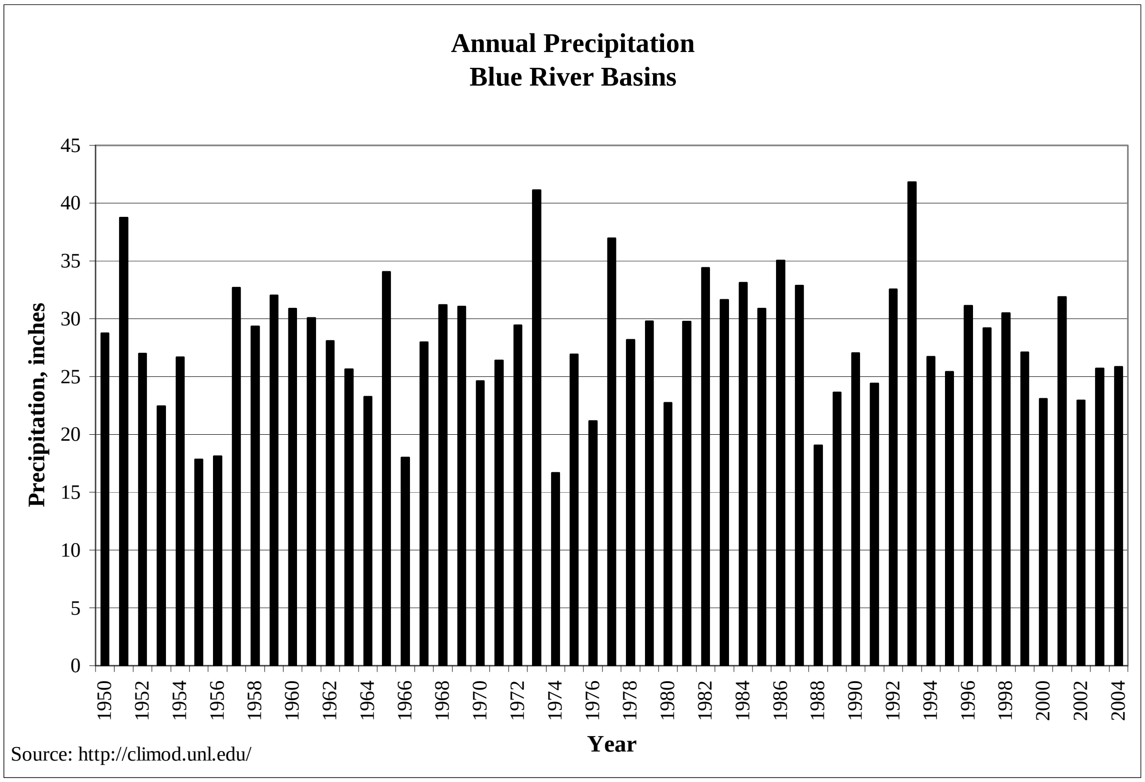
Year	Water Body	Days	Closing Date	Opening Date
1988	Little Blue River Basin	50	Aug 11	Sep 30
1989	Rose Creek	4		
1991	Little Blue River Basin	45	Aug 16	Sep 30
1991	Rose Creek	94	Jun 28	Sep 30
2002	Little Blue River Basin	11	Jul 18	Jul 29
2002	Little Blue River Basin	13	Aug 6	Aug 19
2002	Little Blue River Basin	7	Sep 9	Sep 16
2004	Little Blue River Basin	10	Sep 13	Sep 23
2005	Little Blue River Basin	15	Jul 11	Jul 26
2005	Little Blue River Basin	7	Aug 8	Aug 15

Long-Term Surface Water Supply Evaluation

Future Water Supply

In order to complete the long-term evaluation of surface water supplies, a future 20-year water supply for the basins must be estimated. The basins' water sources are precipitation which runs off as direct streamflow and infiltrates into the ground which discharges as baseflow and ground water movement into the basin which discharges as baseflow. Using methodology published in the Journal of Hydrology (Wen and Chen 2005), a nonparametic Mann-Kendall trend test of the weighted average precipitation in the basins was completed. The analysis showed no statistically significant trend in precipitation ($P > 0.95$) over the past 50 years, Figure B-9. Data does not exist to test whether there is a changing trend in ground water movement into the basin. Therefore using the previous 20 years of streamflow data as the best estimate of the future surface water supply is a reasonable starting point for applying the lag depletions from ground water wells.

Figure B-9. Annual Precipitation, Blue River Basins.



Depletions Analysis

The future depletions that could be expected due to current well development affecting streamflow in the Big Blue River Basin and the glaciated portion of the Little Blue River Basin were not estimated for the same reasons as described in the “Hydrologically Connected Area” subsection above. Even though a MODFLOW ground water model developed by the Upper Big Blue Natural Resources District exists for the other portions of the Little Blue River Basin, it is not sufficient to estimate future depletions at the current time.

Irrigation Surface Water Appropriation Analysis

The comparison of the near-term water supply days available for diversion to the number of days surface water is required to be available to divert 65% and 85% of the net corn crop irrigation requirement are detailed in Tables B-3 and B-4. There is no estimate of the 20-year average days available for diversion in 2031 for the basins due to the inadequacy of current data and models in predicting future stream depletions. Even though the future water supplies were not estimated, the current number of days in which surface water was available for diversion far exceeds the number of days necessary to meet the net corn crop irrigation requirement.

Table B-3. Comparison between the Number of Days Required to Meet the Net Corn Crop Irrigation Requirement and Number of Days Surface Water is Available for Diversion in the Big Blue River Basin.

	Number of Days Necessary to Meet the 65% and 85% of Net Corn Crop Irrigation Requirement	**Near-Term Supply Average Number of Days Available for Diversion (1986-2005)**
July 1 – August 31 (65% Requirement)	23.9	56.1 (32.2 days above the requirement)
May 1 – September 30 (85% Requirement)	31.3	147.1 (115.8 days above the requirement)

Table B-4. Comparison between the Number of Days Required to Meet the Net Corn Crop Irrigation Requirement and Number of Days Surface Water is Available for Diversion in the Little Blue River Basin.

	Number of Days Necessary to Meet the 65% and 85% of Net Corn Crop Irrigation Requirement	**Near-Term Supply Average Number of Days Available for Diversion (1986-2005)**
July 1 – August 31 (65% Requirement)	25.7	54.4 (28.7 days above the requirement)
May 1 – September 30 (85% Requirement)	33.6	142.5 (108.9 days above the requirement)

Ground Water Recharge Sufficiency

The streamflow is not insufficient to sustain over the long term the beneficial uses from wells constructed in aquifers dependent on recharge form the stream (Appendix C).

Sufficiency to Avoid Noncompliance

The State of Nebraska is a signatory member of the Kansas – Nebraska Big Blue River Compact (Compact). The purposes of the Compact are: To promote interstate comity, to achieve an equitable apportionment of the waters of the Big Blue River Basin, to encourage continuation of the active pollution-abatement programs in each of the two states, and to seek further reduction in pollution of the waters of the Big Blue River Basin.

The Compact sets state line flow targets from May 1 through September 30. The state line targets, measured in cubic feet of water per second, are shown in Table B-5. If the flow targets are not met, the State of Nebraska is required to:

1. Limit surface water diversions by natural flow appropriators to their decreed appropriations,
2. Close natural flow appropriators with priority dates junior to November 1, 1968 in accordance with the doctrine of priority,
3. Ensure that no illegal surface water diversions are taking place, and
4. Regulate wells installed after November 1, 1968, within the alluvium and valley side terrace deposits downstream of Turkey Creek in the Big Blue River Basin and downstream of Walnut Creek in the Little Blue River Basin, unless it is determined by the Compact Administration that such regulation would not yield any measurable increase in flows at the state line gage.

At the present time the Compact Administration has found that the regulation of those wells will not yield measurable increases in flow at the state line.

Table B-5. State Line Flow Targets for the Big Blue River.

Month	Big Blue River Target Flow	Little Blue River Target Flow
May	45 cfs	45 cfs
June	45 cfs	45 cfs
July	80 cfs	75 cfs
August	90 cfs	80 cfs
September	65 cfs	60 cfs

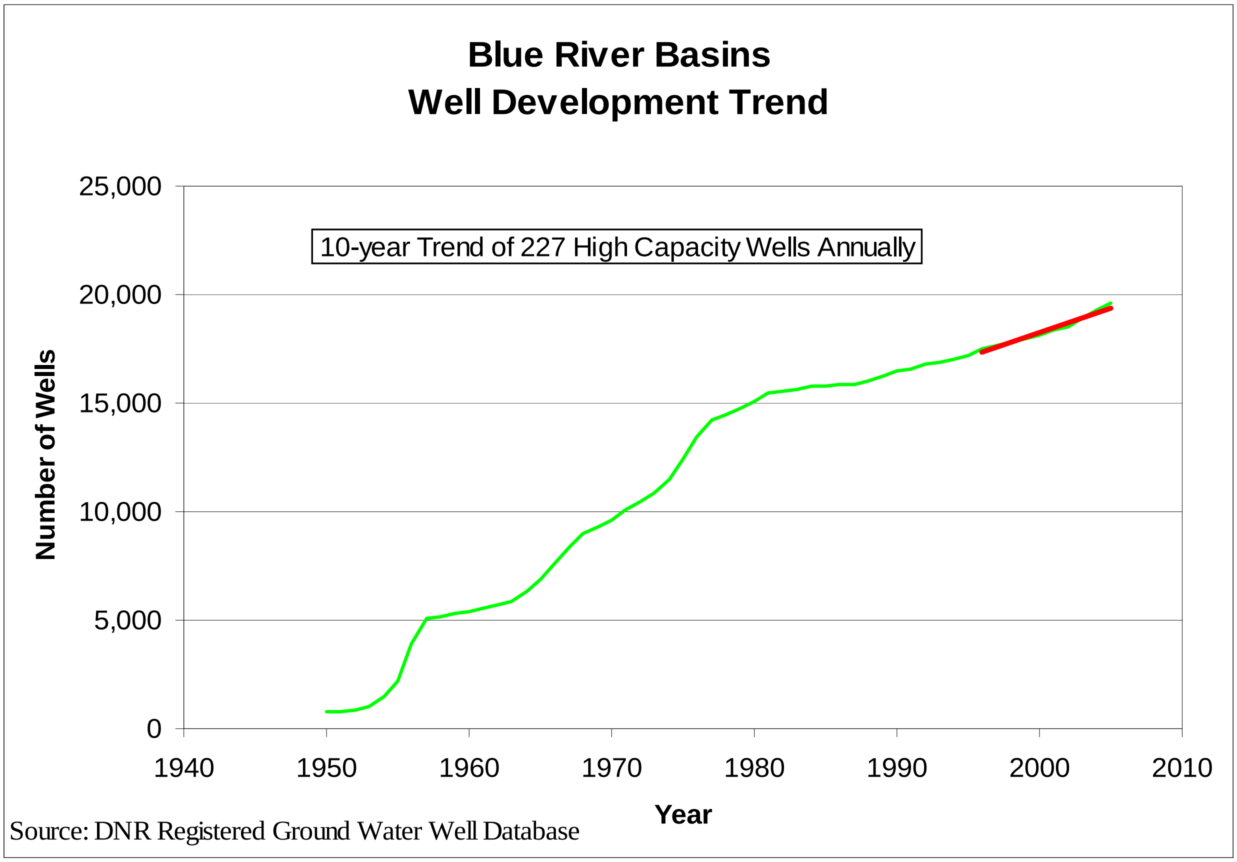
As long as Nebraska administers surface and ground water in compliance with the Compact, decreased streamflow, in and of itself, will not cause Nebraska to be in noncompliance; therefore, any depletion would not cause Nebraska to be in noncompliance. However, decreased streamflows could increase the number of times the state would have to administer water to remain in compliance.

Future Development

Estimates of the number of high capacity wells (wells pumping greater than 50 gallons per minute) that would be completed over the next 25 years if no new legal constraints on the construction of such wells were imposed were calculated based on extrapolating the present day rate of increase in well development into the future, Figure B-10. For the past 10 years, the rate of increase in high capacity wells is linear at a rate of 227 wells per year in the basins.

For reasons the same as stated above in the “Depletions Analysis” subsection of this section, no estimates of depletions due to current and future ground water development were computed. Even though the effects on future water supplies were not estimated, the current number of days in which surface water was available for diversion far exceeds the number of days necessary to meet the net corn crop irrigation requirement.

Figure B-10. High Capacity Well Development, Blue River Basins.



The future water supply in the basins actually may improve in the future if water can be made available to augment state line flows to meet Compact targets. A cooperative study between the Department, the U.S. Bureau of Reclamation, and the Basin NRDs is examining the value of augmentation water and identifying potential projects to supply augmentation water.

Future Analysis

The complexity of the basins requires more sophisticated efforts in investigating the impacts of anthropogenic activities on ground water and surface water relations and water supply. Starting in 2005, development of a ground water model for the Big Blue and Little Blue River Basins was begun by the NRDs within those basins. This work is an expansion of the ground water model developed by the Upper Big Blue NRD for the 2006 report. It will utilize new hydrogeologic mapping and related information being collected for this effort. The anticipated date for release of this model is post 2006.

Conclusions

Based upon available information and its evaluation, the Department has reached a preliminary conclusion that the surface water and ground water supplies in hydrologic connection to the surface water supplies in the Blue River basins are not fully appropriated. The best available data does not allow for analysis of whether or not this determination would change if no additional legal constraints are imposed on future development of hydrologically connected surface water and ground water.

Bibliography of Hydrogeologic References for Big and Little Blue River Basins

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Wen, F.J., and X.H. Chen. 2005. Streamflow trends and depletion study in Nebraska with a focus on the Republican River Basin. *Water Resources Research* (In Review).

Lower Niobrara River Basin

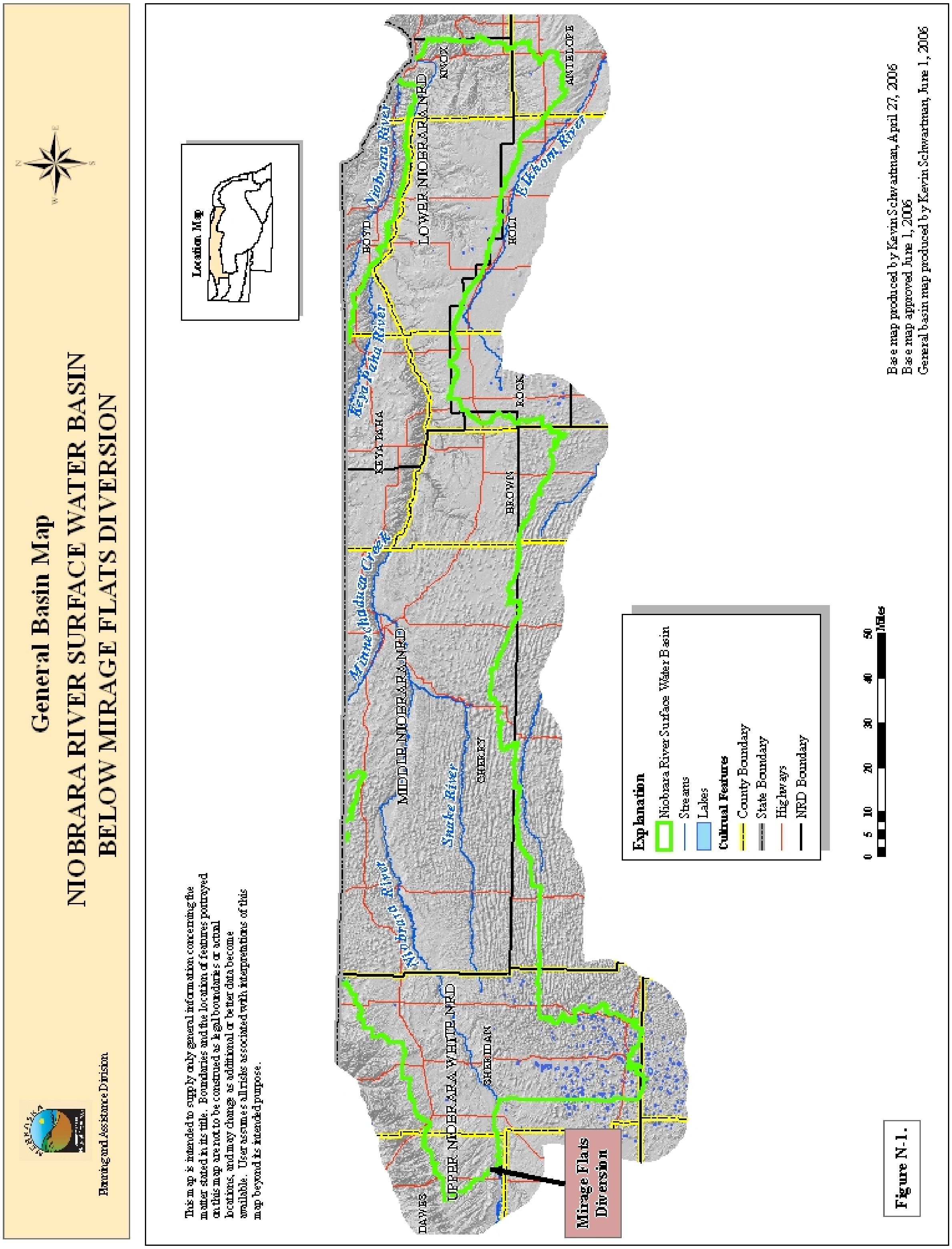
Summary

Based on the analysis of the sufficiency of the long-term surface water supply in the Lower Niobrara River Basin, the Department has reached a preliminary conclusion that the basin is not fully appropriated. Even though the effects of future ground water development on future water supplies were not estimated in the basin, the current number of days in which surface water was available for diversion far exceeds the number of days necessary to meet the net corn crop irrigation requirement. The best available data does not allow for analysis of whether or not this determination would change if no additional legal constraints are imposed on future development.

Basin Description

The Lower Niobrara River Basin in Nebraska is defined as the surface areas in Nebraska that drain into the Niobrara River Basin that had not previously been determined to be fully appropriated. This area extends from the Mirage Flats Diversion Dam in the west to the confluence of the Niobrara River and the Missouri River. It includes all areas of ground water which impact surface water flows in the basin, Figure 1. The total area of the Niobrara River surface water basin is approximately 8,900 square miles. Natural Resources Districts with significant areas in the basins are the Upper Niobrara White Natural Resources District, the Middle Niobrara Natural Resources District, and the Lower Niobrara Natural Resources District.

Figure N-1. General Basin Map, Lower Niobrara River Basin.



Nature and Extent of Water Use

Ground Water

Ground water in the basin is used for a variety of purposes: domestic, industrial, livestock, irrigation, and other uses. There are a total of 6,822 registered ground water wells within the basin as of December 31, 2005 (Department registered ground water wells database), with an estimated 350 ground water wells to be developed during 2006, Figure N-2. The locations of all active ground water wells can be seen in Figure N-3.

Figure N-2. Current Well Development by Number of Registered Wells, Lower Niobrara River Basin.

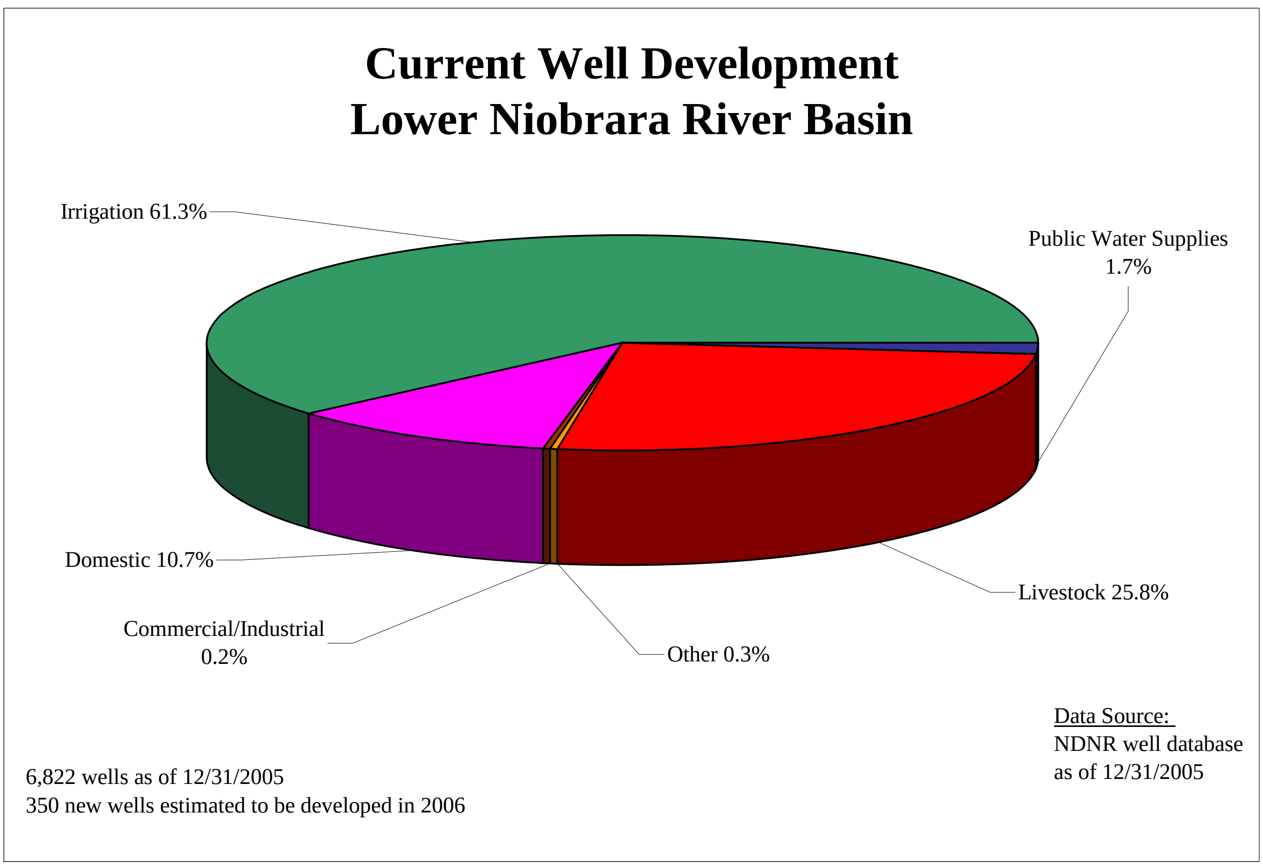
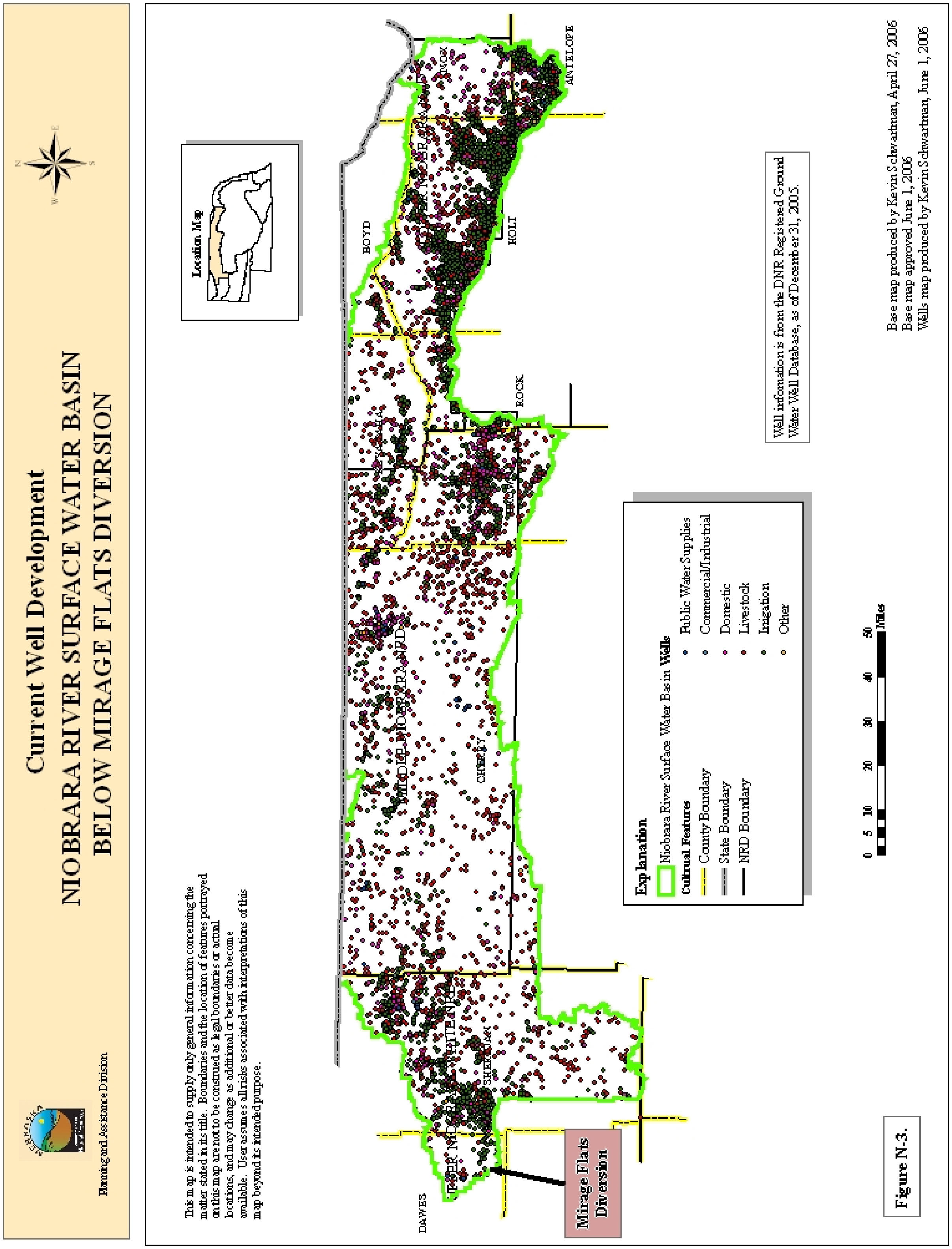


Figure N-3. Current Well Locations, Lower Niobrara River Basin.



Surface Water

As of December 31, 2005, there were 837 surface water appropriations in the basin issued for a variety of uses, Figure N-4. The majority of the surface water appropriations are for irrigation use and storage and tend to be located on the major streams. There is an instream flow appropriation in the basin located on Long Pine Creek. The first surface water appropriations in the basin were permitted in 1894 and development has continued through present day. The approximate locations of the surface water diversions are shown in Figure N-5.

Figure N-4. Surface Water Appropriations by Number of Diversion Points, Lower Niobrara River Basin.

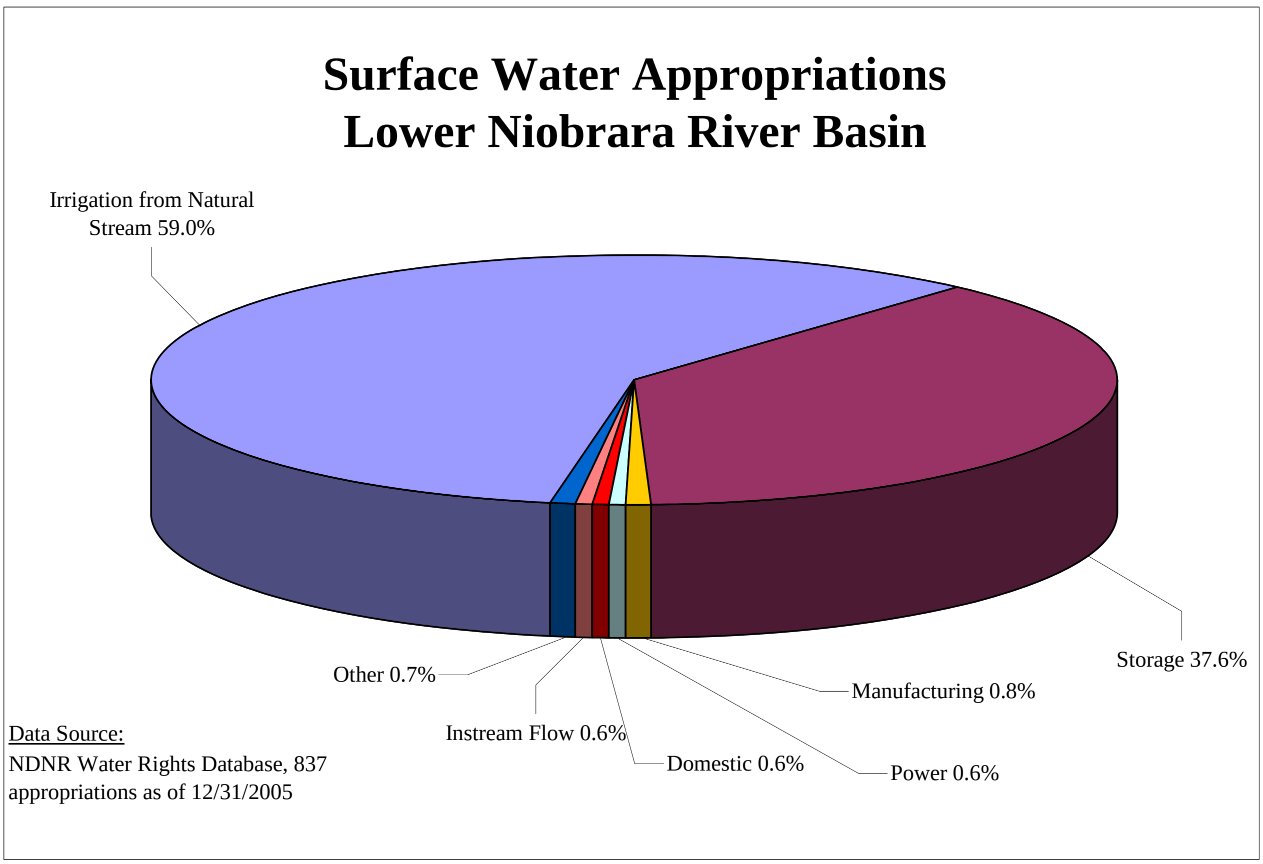
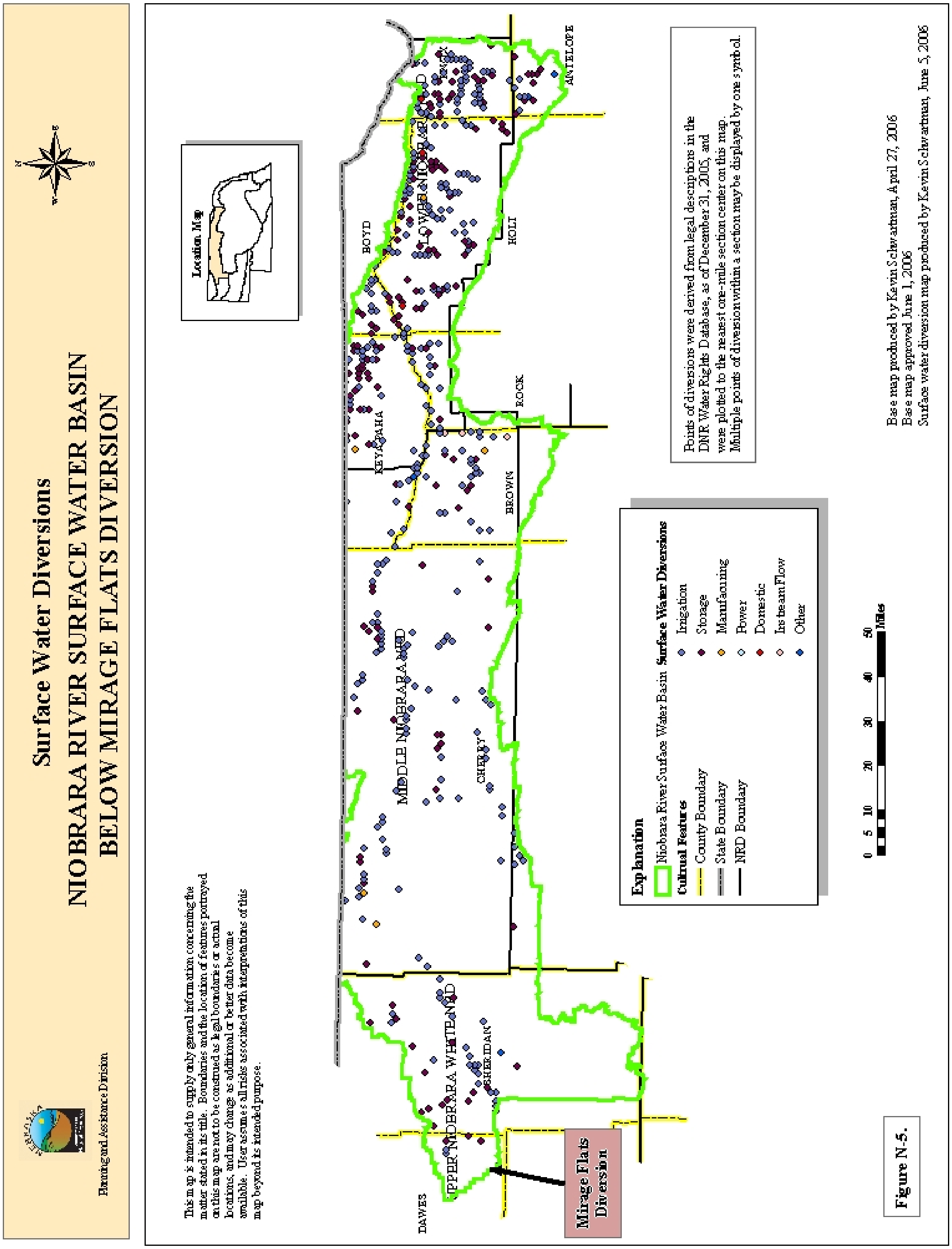


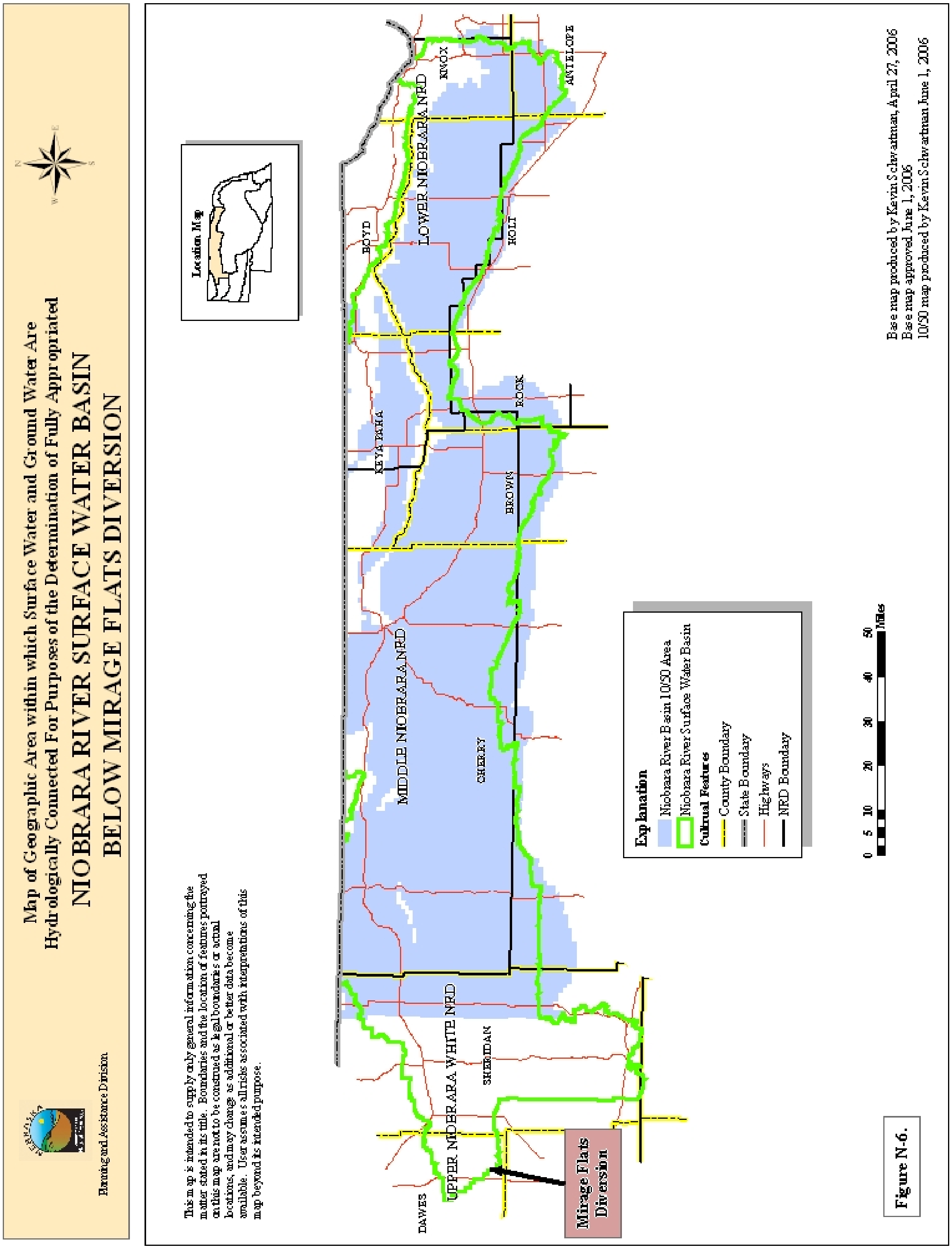
Figure N-5. Surface Water Appropriation Diversion Locations, Lower Niobrara River Basin.



Hydrologically Connected Area

No sufficient numeric ground water model is available in the Lower Niobrara River Basin to determine the 10 percent depletion in 50-year area (10/50 area). Therefore, the 10/50 area was determined using stream depletion factor (SDF) methodology. Figure N-6 specifies the extent of the 10/50 area. A description of the SDF methodology used appears in the methodology section of this report.

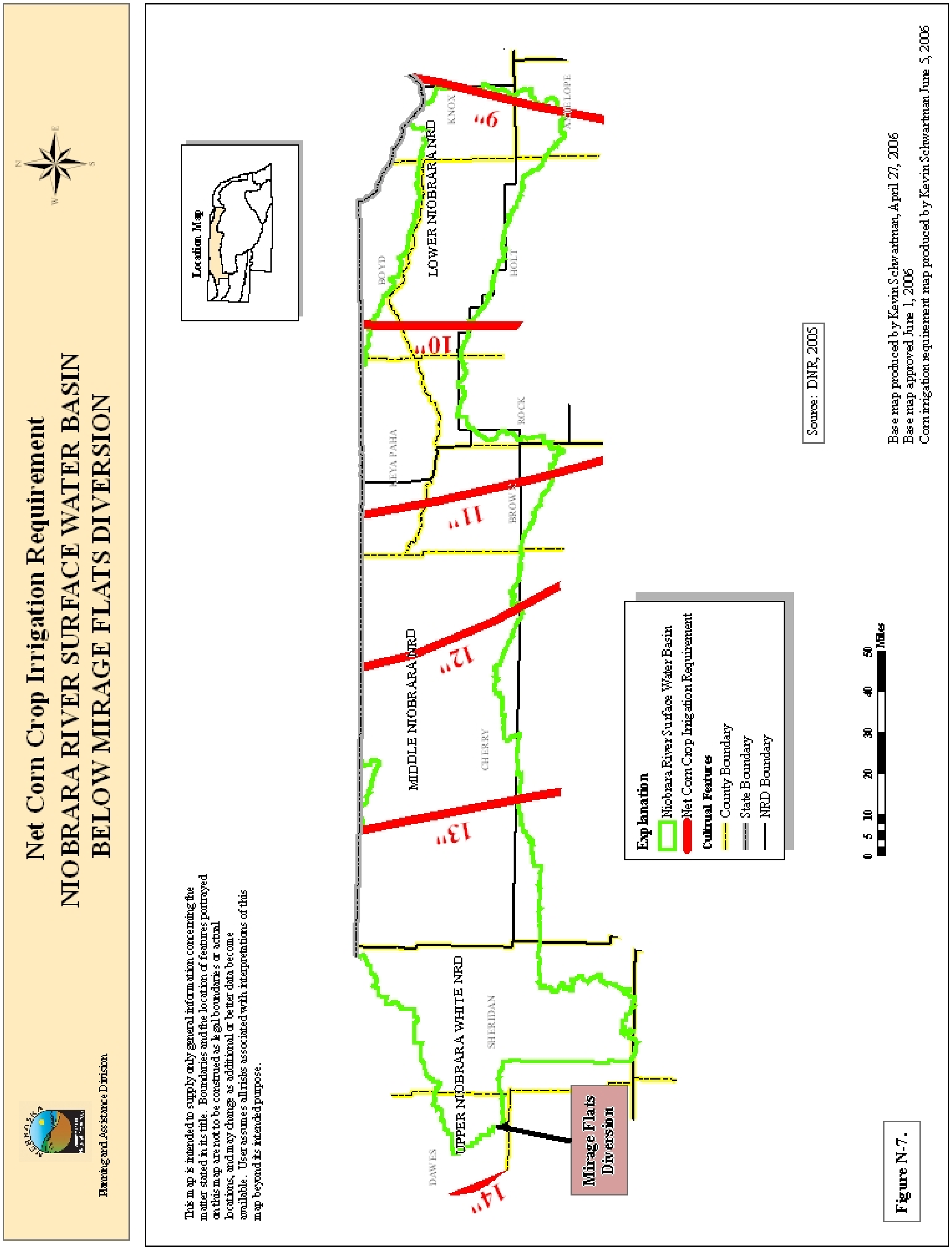
Figure N-6. 10/50 Area, Lower Niobrara River Basin.



Net Corn Crop Irrigation Requirement

Figure N-7 is a map of the net corn crop irrigation requirement for the basin (DNR 2005). The net corn crop irrigation requirement in the basin ranges from 8.9 to 13.9 inches. Assuming a surface water diversion rate equal to 1 cubic foot per second (cfs) per 70 acres and a downtime value of 10 percent, it will take between 23.6 and 36.9 days annually to divert 65% of the net corn crop irrigation requirement and between 30.9 and 48.3 days to divert 85% of the net corn crop irrigation requirement.

Figure N-7. Net Corn Crop Irrigation Requirement, Lower Niobrara River Basin.



Surface Water Closing Records

Table N-1 records all surface water administration that has occurred in the basin between 1986 and 2005.

Table N-1. Surface Water Administration in the Lower Niobrara River Basin, 1986-2005.

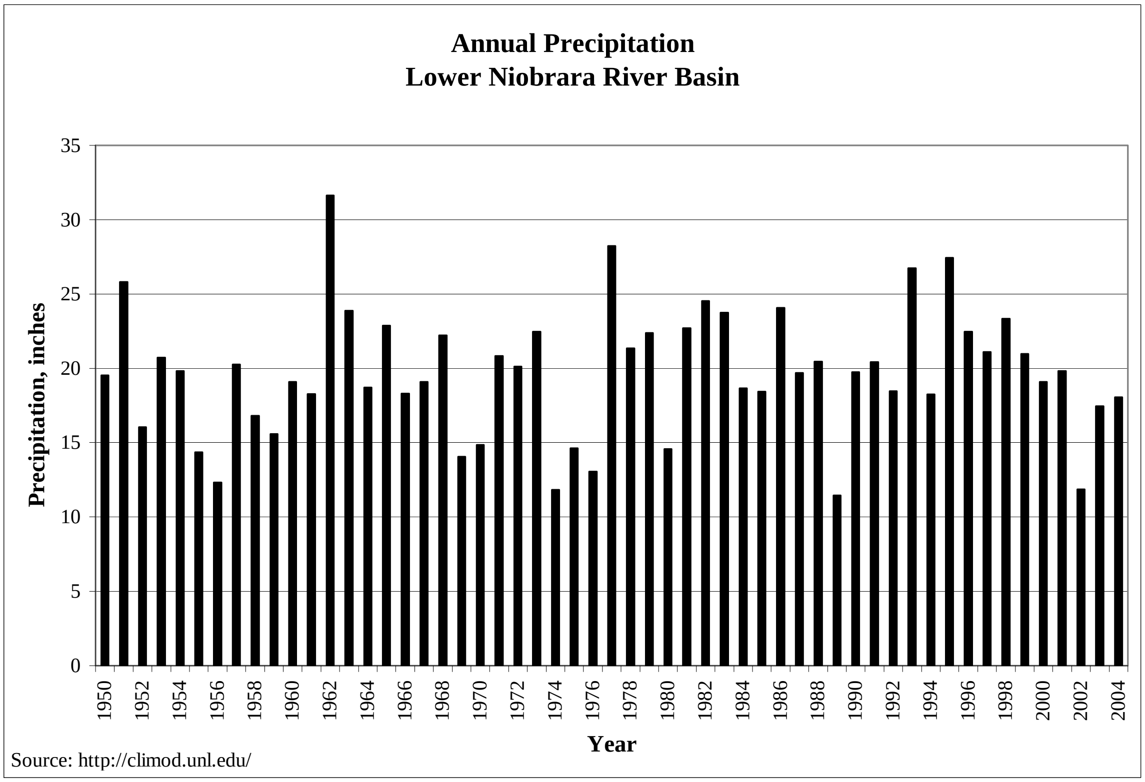
Year	Water Body	Days	Closing Date	Opening Date
1991	North Branch Verdigree Creek	3	Jul 26	Jul 29

Long-Term Surface Water Supply Evaluation

Future Water Supply

In order to complete the long-term evaluation of surface water supplies, a future 20-year water supply for the basin must be estimated. The basin's water sources are precipitation which runs off as direct streamflow and infiltrates into the ground which discharges as baseflow, ground water movement into the basin which discharges as baseflow, and streamflow from the upper Niobrara River. Using methodology published in the Journal of Hydrology (Wen and Chen 2005), a nonparametic Mann-Kendall trend test of the weighted average precipitation in the basin was completed. The analysis showed no statistically significant trend in precipitation ($P > 0.95$) over the past 50 years, Figure N-8.   No statistical analyses of the ground water movement into the basin or streamflows from the upper Niobrara River were made due to the lack of data. Therefore using the previous 20 years of streamflow data as the best estimate of the future surface water supply is a reasonable starting point for applying the lag depletions from ground water wells.

Figure N-8. Annual Precipitation, Lower Niobrara River Basin.



Depletions Analysis

The future depletions that could be expected due to current well development affecting streamflow in the basin were estimated using SDF methodology as documented in the methodology section. The results estimate the future streamflow at the mouth of the Niobrara River to be depleted by 25 cfs in 10 years, 30 cfs in 15 years, 35 cfs in 20 years and 40 cfs in 25 years.

Irrigation Surface Water Appropriation Analysis

The comparison of the near-term water supply days available for diversion to the number of days surface water is required to be available to divert 65% and 85% of the net corn crop irrigation requirement are detailed in Table N-2. There is no estimate of the 20-year average days available for diversion in 2031 for the basin because there has been no surface water administration on the Niobrara River itself. Even though the future water supplies were not estimated, the current number of days in which surface water was available for diversion far exceeds the number of days necessary to meet the net corn crop irrigation requirement.

Table N-2. Comparison between the Number of Days Required to Meet the Net Corn Crop Irrigation Requirement and Number of Days Surface Water is Available for Diversion, Lower Niobrara River Basin.

	Number of Days Necessary to Meet the 65% and 85% of Net Corn Crop Irrigation Requirement	**Near-Term Supply Average Number of Days Available for Diversion (1986-2005)**
July 1 – August 31 (65% Requirement)	23.6 to 36.9	61.9 or greater (at least 23.7 days above the requirement)
May 1 – September 30 (85% Requirement)	30.9 to 48.3	152.9 or greater (at least 102.9 days above the requirement)

Instream Flow Surface Water Appropriation Analysis

The future surface water supply for instream flow surface water appropriations in the basin were evaluated by applying the erosion rule on a monthly basis. The 20-year estimate of the future average number of days when the instream flow appropriation would be met at the time of the appropriation application was compared to the 20-year average estimate of the number days when the instream flow appropriations would be met using the future depleted surface water supply. The results are shown in Table N-3. Results show no erosion in any month. The long-term surface water supply in the basin is sufficient for the instream flow appropriations in the basin.

Table N-3. Long Pine Creek Instream Flow Appropriation Evaluation

Month	Estimate of Future Days When Flows Met at Time of Application	Estimate of Future Days Flows Met Using Long-Term Water Supply
October	31.0	31.0
November	30.0	30.0
December	31.0	31.0
January	31.0	31.0
February	28.0	28.0
March	31.0	31.0
April	30.0	30.0
May	31.0	31.0
June	30.0	30.0
July	31.0	31.0
August	31.0	31.0
September	30.0	30.0

Ground Water Recharge Sufficiency

The streamflow is not insufficient to sustain over the long term the beneficial uses from wells constructed in aquifers dependent on recharge from the stream (Appendix C).

Sufficiency to Avoid Noncompliance

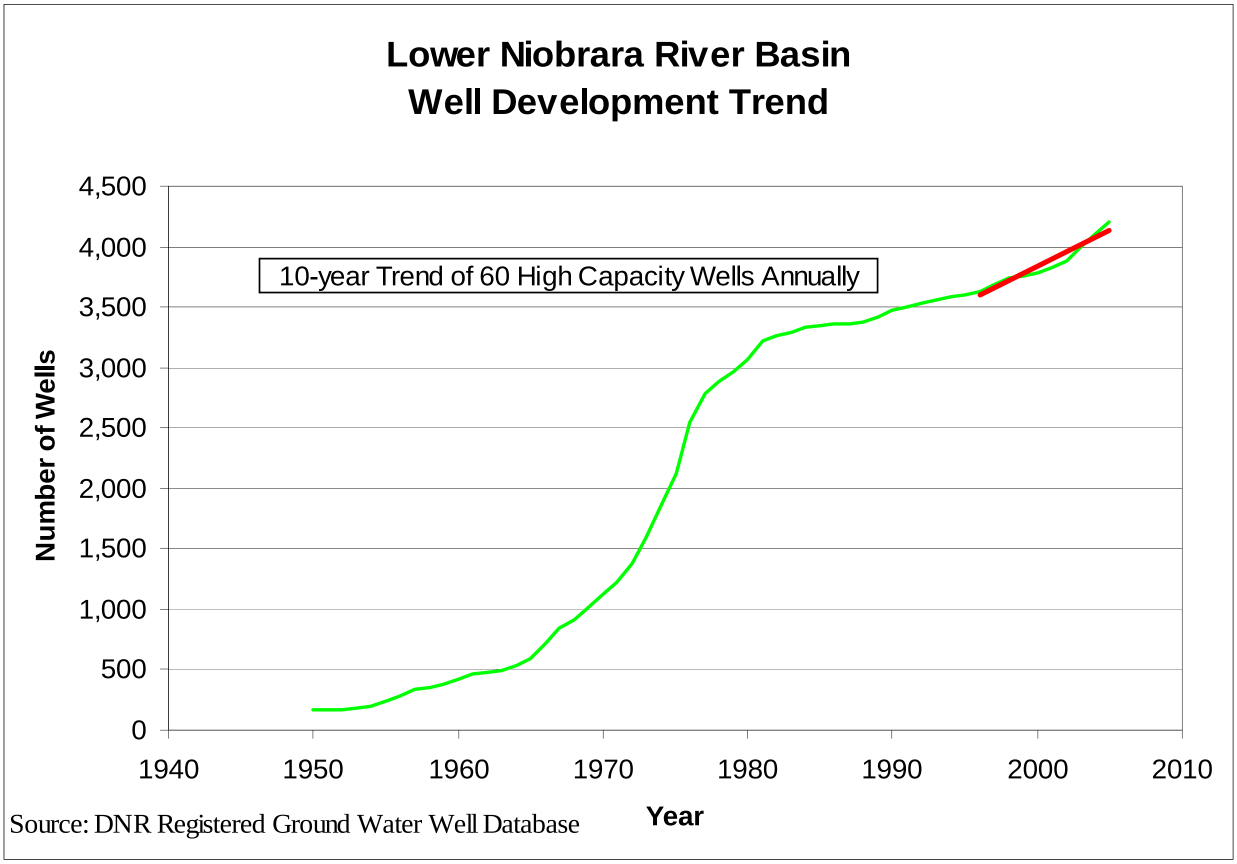
There are no compacts on any portions of the Lower Niobrara River Basin in Nebraska.

Future Development

Estimates of the number of high capacity wells (wells pumping greater than 50 gallons per minute) that would be completed over the next 25 years if no new legal constraints on the construction of such wells were imposed were calculated based on extrapolating the present day rate of increase in well development into the future, Figure N-9. For the past 10 years, the rate of increase in high capacity wells is linear at a rate of 60 wells per year.

For the depletion analysis, it is assumed that further ground water development will most likely be in the form of high capacity wells for irrigation purposes. Each future development well was placed in an area where the soil is classified as irrigable by the United States Department of Agriculture and at least 1,400 feet away from existing high capacity wells, which is the slightly larger than the radius of an average center pivot.

Figure N-9. High Capacity Well Development, Lower Niobrara River Basin.



The future depletions that could be expected due to current and future well development affecting streamflow in the basin were estimated using SDF methodology. The results estimate the future streamflow at the mouth of the Niobrara to be depleted by 40 cfs in 10 years, 65 cfs in 15 years, 90 cfs in 20 years and 115 cfs in 25 years. Even though the future water supplies were not estimated, the current number of days in which surface water was available for diversion far exceeds the number of days necessary to meet the net corn crop irrigation requirement.

Future Analysis

A substantial portion of the Niobrara River Basin on the south side of the river is included in the Elkhorn-Loup ground water model (ELM) which is currently being developed for evaluating the ground water-surface water relationship and water supply of the Elkhorn and Loup River Basins. Although not developed to specifically evaluate water supply for the Niobrara River Basin, this model can be adapted to analyze water resources in the basin. Efforts will be made to incorporate results from this model in future reports.

Conclusions

Based upon available information and its evaluation, the Department has reached a preliminary conclusion that the Lower Niobrara River Basin is not fully appropriated. The best available data does not allow for analysis of whether or not this determination would change if no additional legal constraints are imposed on future development of hydrologically connected surface water and ground water.

Bibliography of Hydrogeologic References for Lower Niobrara River Basin

Conservation and Survey Division. 2005. *Mapping of Aquifer Properties-Transmissivity and Specific Yield-for Selected River Basins in Central and Eastern Nebraska.* Lincoln.

Nebraska Department of Natural Resources. 2005. *2006 Annual Evaluation of Availability of Hydrologically Connected Water Supplies*. Lincoln, Nebraska: Department of Natural Resources.

Wen, F.J., and X.H. Chen. 2005. Streamflow trends and depletion study in Nebraska with a focus on the Republican River Basin. *Water Resources Research* (In Review).

Lower Platte River Basin

Summary

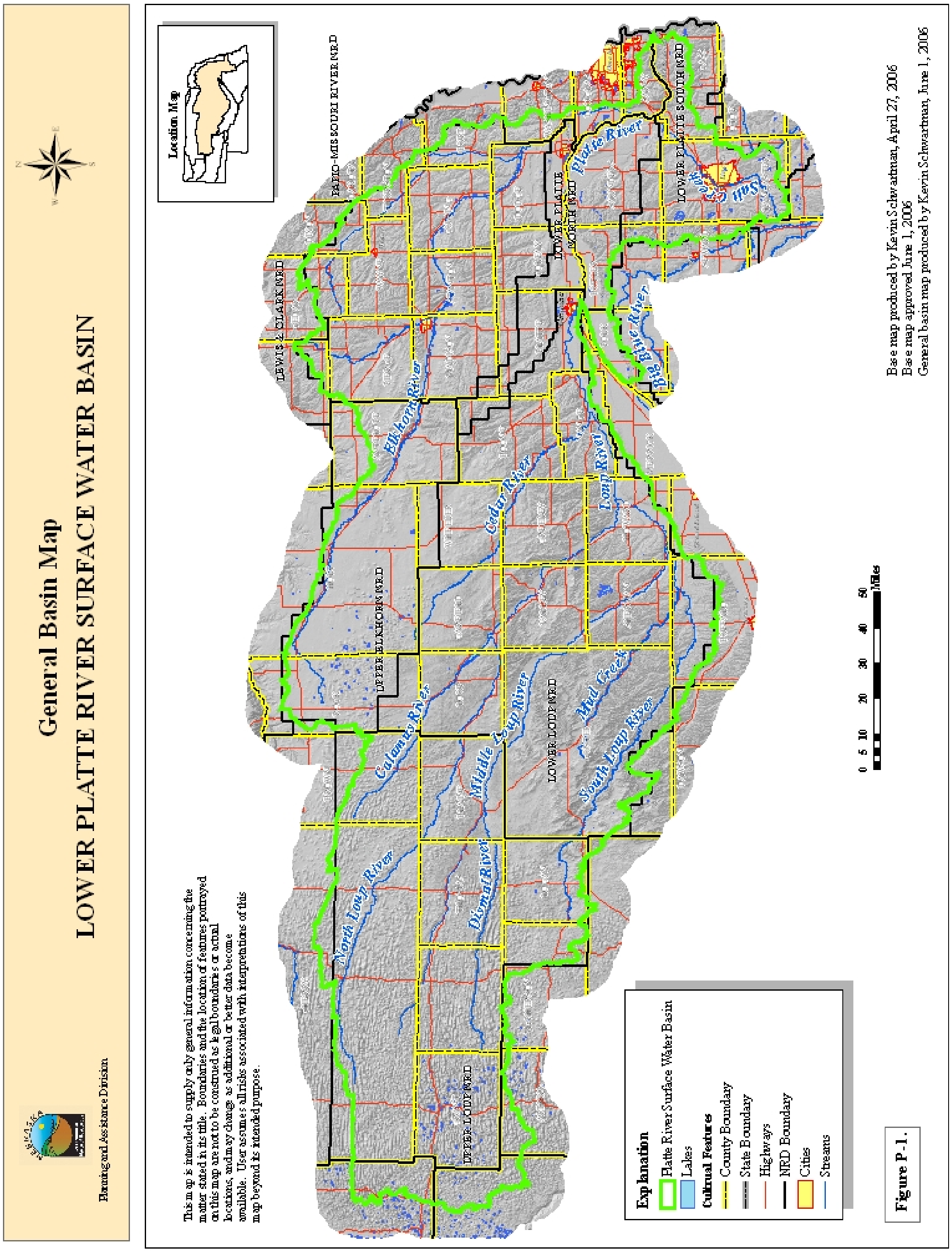
Based on the analysis of the sufficiency of the long-term surface water supply in the Lower Platte River Basin, the Department has reached a preliminary conclusion that without the initiation of additional uses, the basin is not presently fully appropriated. However, based on reasonable projections of the extent and location of future development in the basin and current available data, the analysis also shows that this preliminary conclusion would change to a conclusion that the subbasin of the Platte River Basin above the North Bend gage is fully appropriated if no additional constraints are placed on surface water and ground water development.

Basin Description

The Lower Platte River is defined as the reach of the Platte River from its confluence with the Loup River to its confluence with the Missouri River. The Lower Platte River Basin is defined as all surface areas that drain into the Lower Platte River including those areas that drain into the Loup River and the Elkhorn River, Figure P-1, and all areas of ground water which impact surface water flows of the basin. The total area of the Lower Platte River surface water basin is approximately 25,400 square miles of which approximately 15,200 square miles are in the Loup River subbasin and approximately 7,000 square miles are in the Elkhorn River subbasin. Natural Resources Districts with significant areas in the basin are the Lower Platte South Natural Resources District, Lower Platte North Natural Resources District, the Upper Elkhorn Natural

Resources District, the Lower Elkhorn Natural Resources District, the Upper Loup Natural Resources District, the Lower Loup Natural Resources District, and the Papio-Missouri River Natural Resources District. Portions of the Central Platte Natural Resources District are included in the basin, but are not being evaluated because all of the Central Platte Natural Resources District is already included in an integrated management planning process.

Figure P-1. General Basin Map, Lower Platte River Basin.



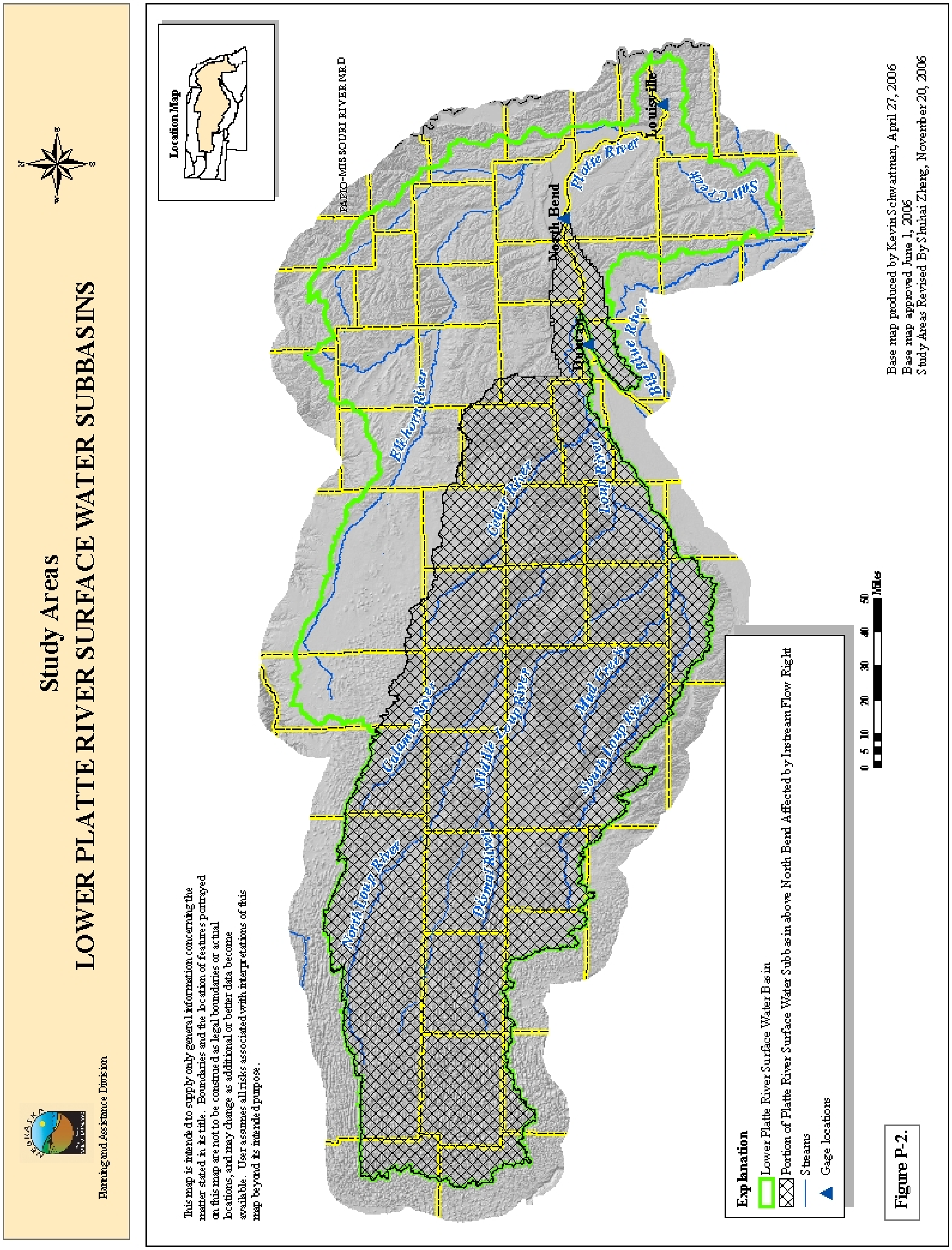
Subbasin Relationships

When considering the Lower Platte River Basin, it is important to understand the relationship between the senior appropriations and the junior surface water appropriations in the Loup and Elkhorn River subbasins. In general, whenever a senior water right is calling for water, all water rights upstream from the senior can be shut off to get water to the senior appropriator. Starting with the most junior appropriator, the Department will shut off as many junior appropriators as necessary to provide water to the senior appropriator. In the Lower Platte River Basin the instream flow rights, with a priority date of 1993, are the primary senior rights causing the need for water administration. The instream flow appropriations are measured at the North Bend gage and the Louisville gage. When instream flow appropriations are not met at the North Bend gage, all junior surface water appropriations above that gage, including those in the Loup River Basin, are closed to diversion (Figure P-2). When instream flow appropriations are not met at the Louisville gage, all junior surface water appropriations above that gage, including those in the Loup and Elkhorn River subbasins, are closed to diversion. Even if the instream flow appropriation is being met at the North Bend gage, the junior surface water appropriations upstream of that gage will still be closed if the instream flow appropriation is not being met at the Louisville gage. Administration for the instream flow rights did not begin until 1997. Therefore to evaluate a 20 year record, the Department had to determine how many days there would have been administration if the instream flow rights had been in existence for the entire period. Between 1986 and 2005, the junior surface water appropriations in the Platte River, Loup River, and Elkhorn River subbasin would have been closed due to the instream flow appropriations not being met during July and August a total of 530 days. Of the 530 days, the cause for being closed was:

- both the North Bend and Louisville instream appropriation not being met - 383 days,
- the North Bend instream appropriation not being met even though the Louisville instream flow appropriation was being met - 37 days, and
- the Louisville instream appropriation not being met, even though the North Bend instream flow appropriation was being met - 110 days.

Thus development in the basin below the North Bend gage, including the Elkhorn River subbasin, could continue to deplete streamflows at the Louisville gage to the detriment of those junior surface water appropriations in the Loup River Basin.

Figure P-2 Map of Subbasin of the Platte River Basin above the North Bend Gage



Nature and Extent of Water Use

Ground Water

Ground water in the basin is used for a variety of purposes: domestic, industrial, livestock, irrigation, and other uses. There are a total of 40,800 registered ground water wells within the basin as of December 31, 2005 (Department registered ground water wells database), with an estimated 1,900 ground water wells to be developed during 2006, Figure P-3. The locations of all active ground water wells can be seen in Figure P-4.

Figure P-3. Current Well Development by Number of Registered Wells, Lower Platte River Basin.

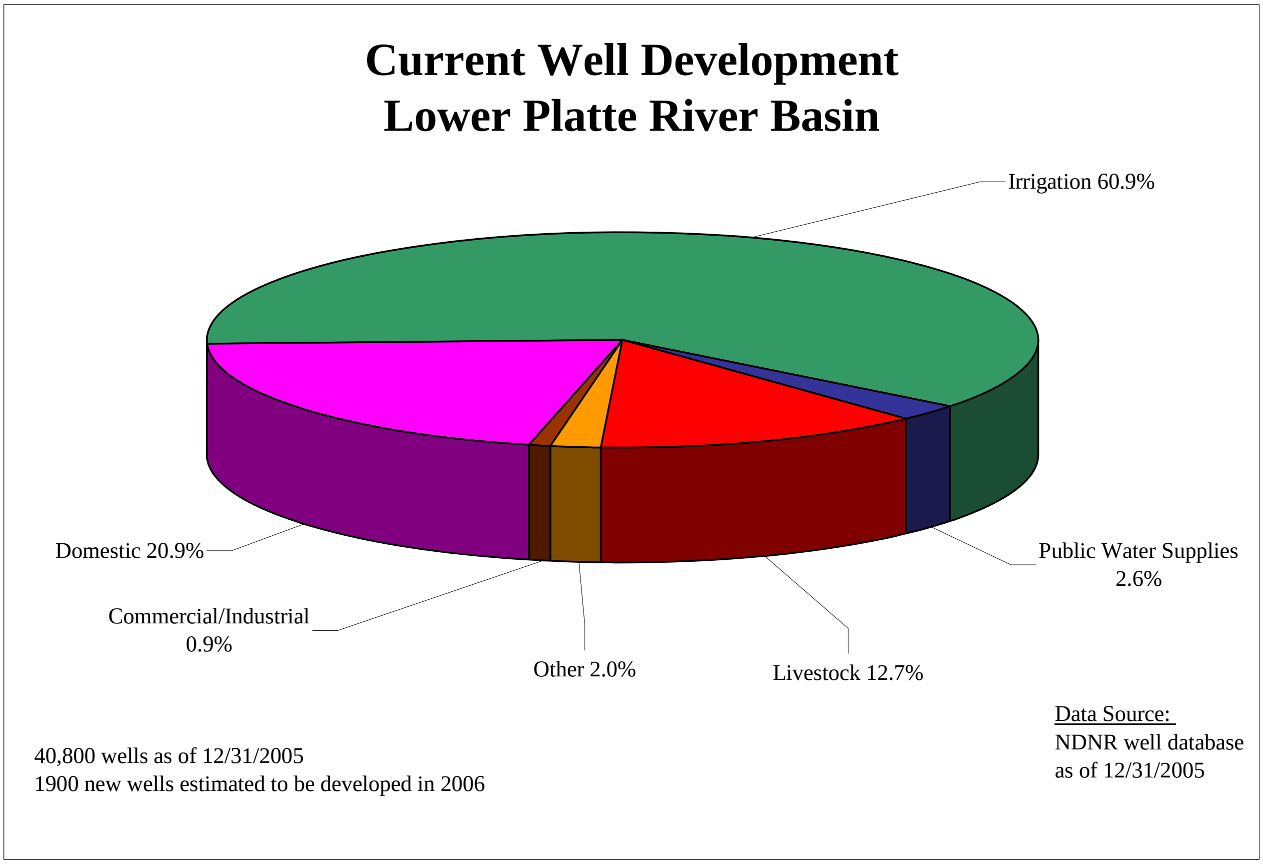
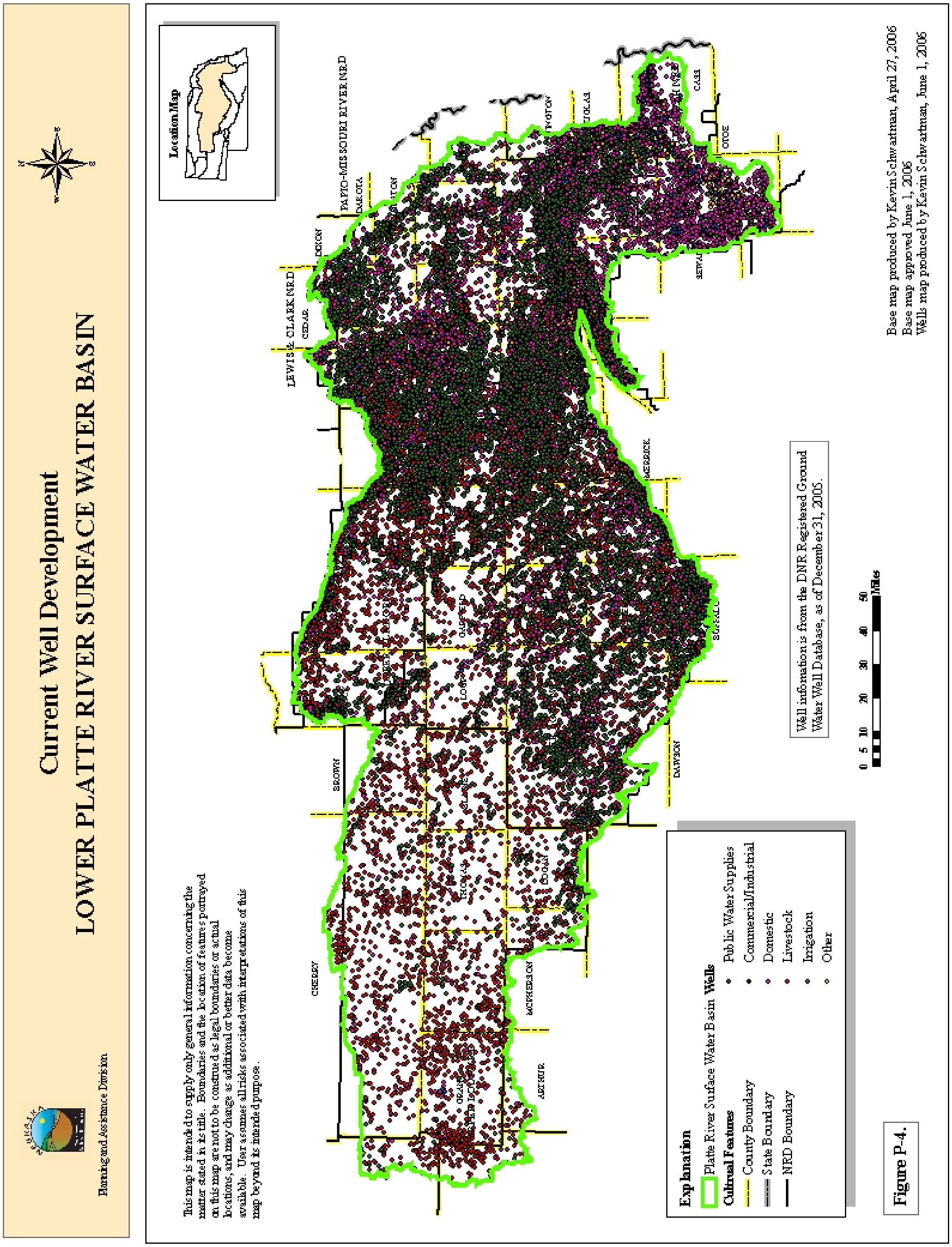


Figure P-4. Current Well Locations, Lower Platte River Basin.



Surface Water

As of December 31, 2005, there were 2,751 surface water appropriations in the basin issued for a variety of uses, Figure P-5. The majority of the surface water appropriations are for irrigation use and tend to be located on the major streams. There are two instream flow appropriations in the basin located on the Platte River at North Bend and Louisville. The first surface water appropriations in the basin were permitted in 1890 and development has continued through present day. The approximate locations of the surface water diversions are shown in Figure P-6.

Figure P-5. Surface Water Appropriations by Number of Diversion Points, Lower Platte River Basin.

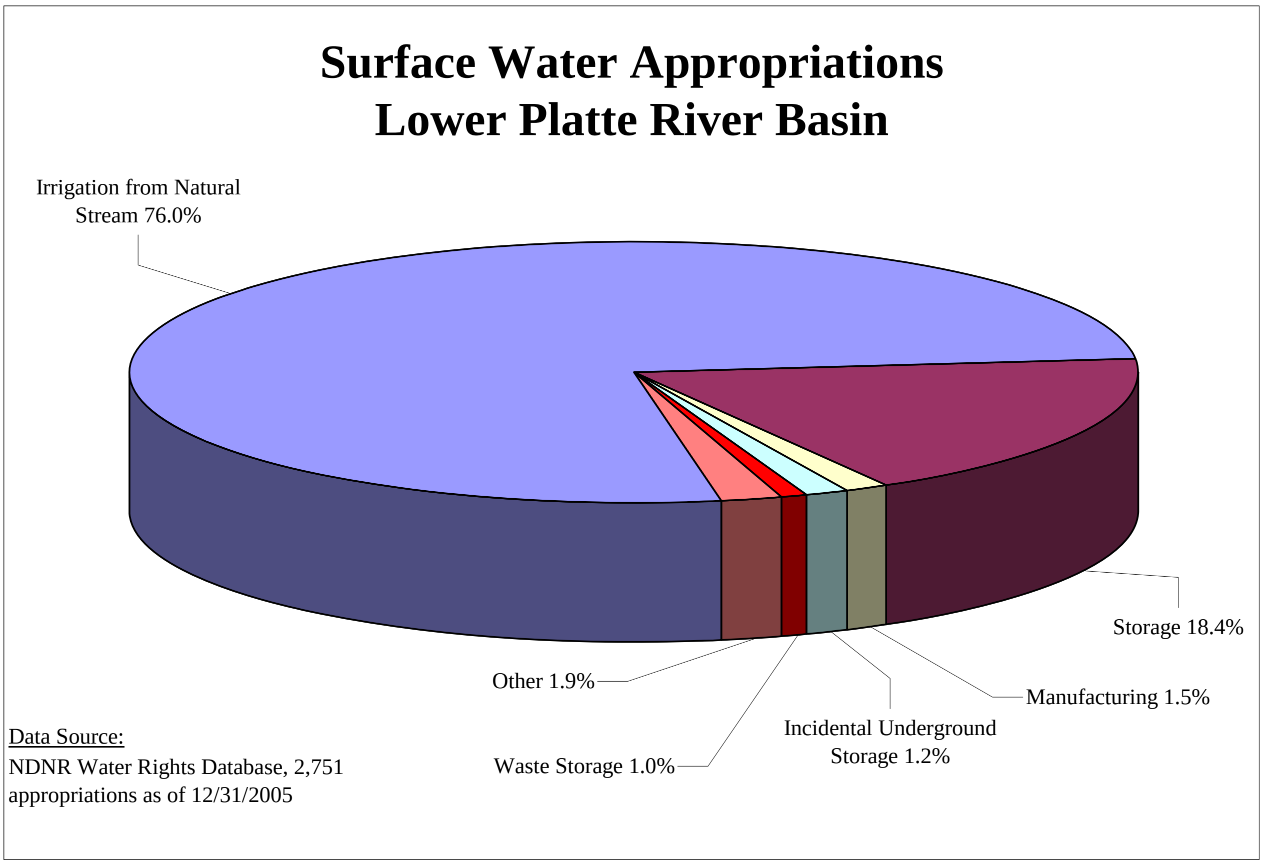
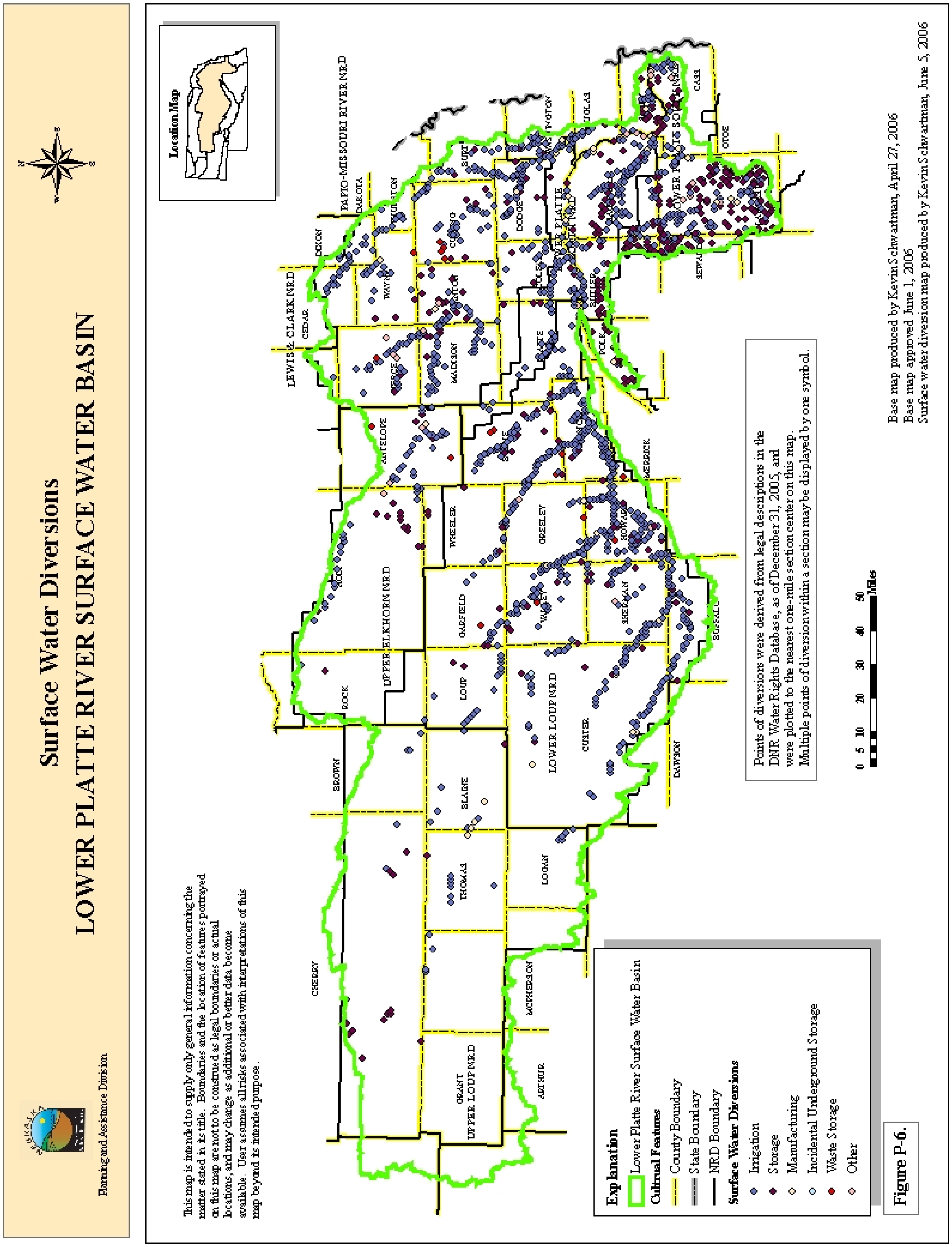


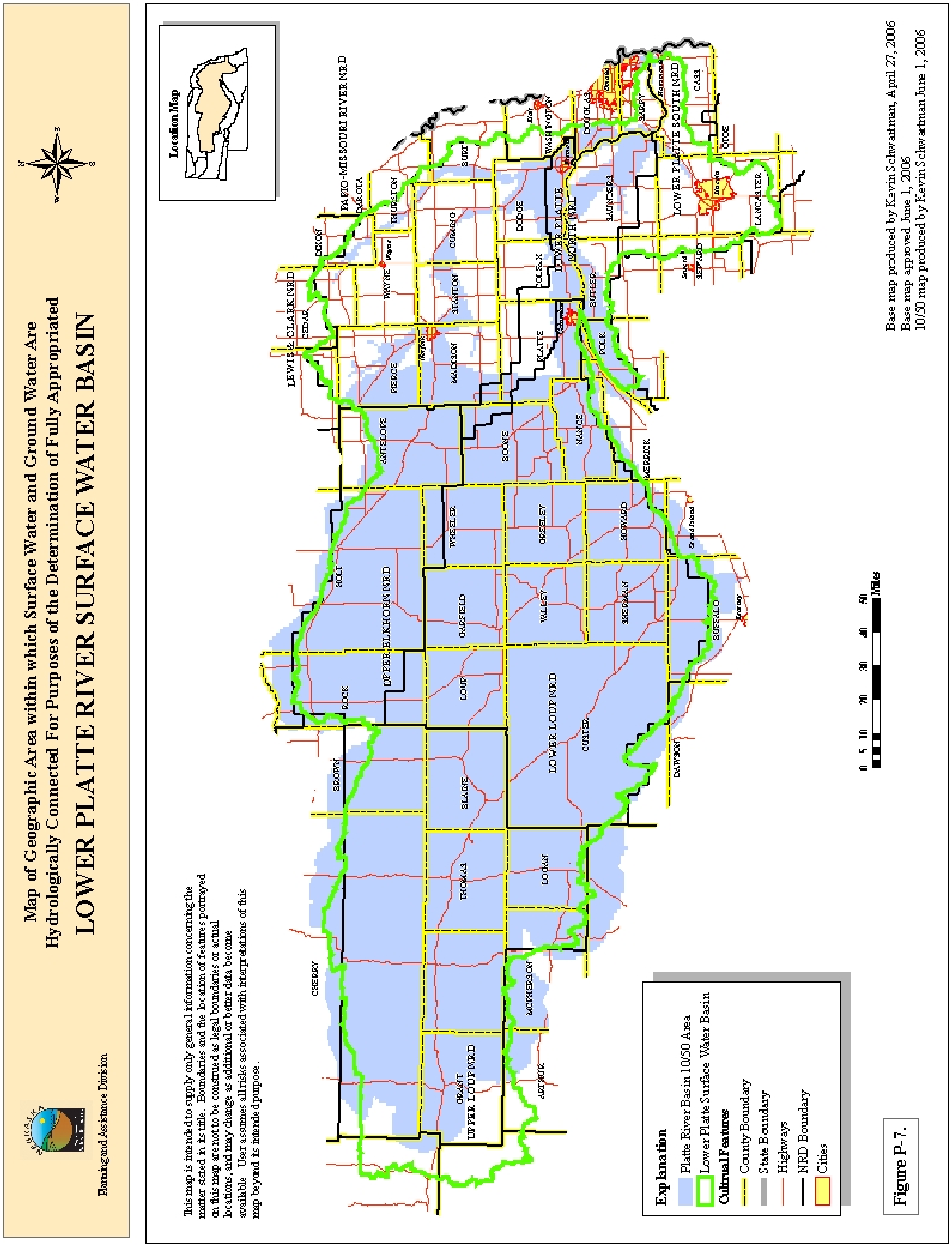
Figure P-6. Surface Water Appropriation Diversion Locations, Lower Platte River Basin.



Hydrologically Connected Area

No sufficient numeric ground water model is available in the Lower Platte River Basin to determine the 10 percent depletion in 50-year area (10/50 area). Therefore, the 10/50 area was determined using stream depletion factor (SDF) methodology. Figure P-7 specifies the extent of the 10/50 area. A description of the SDF methodology used appears in the methodology section of this report.

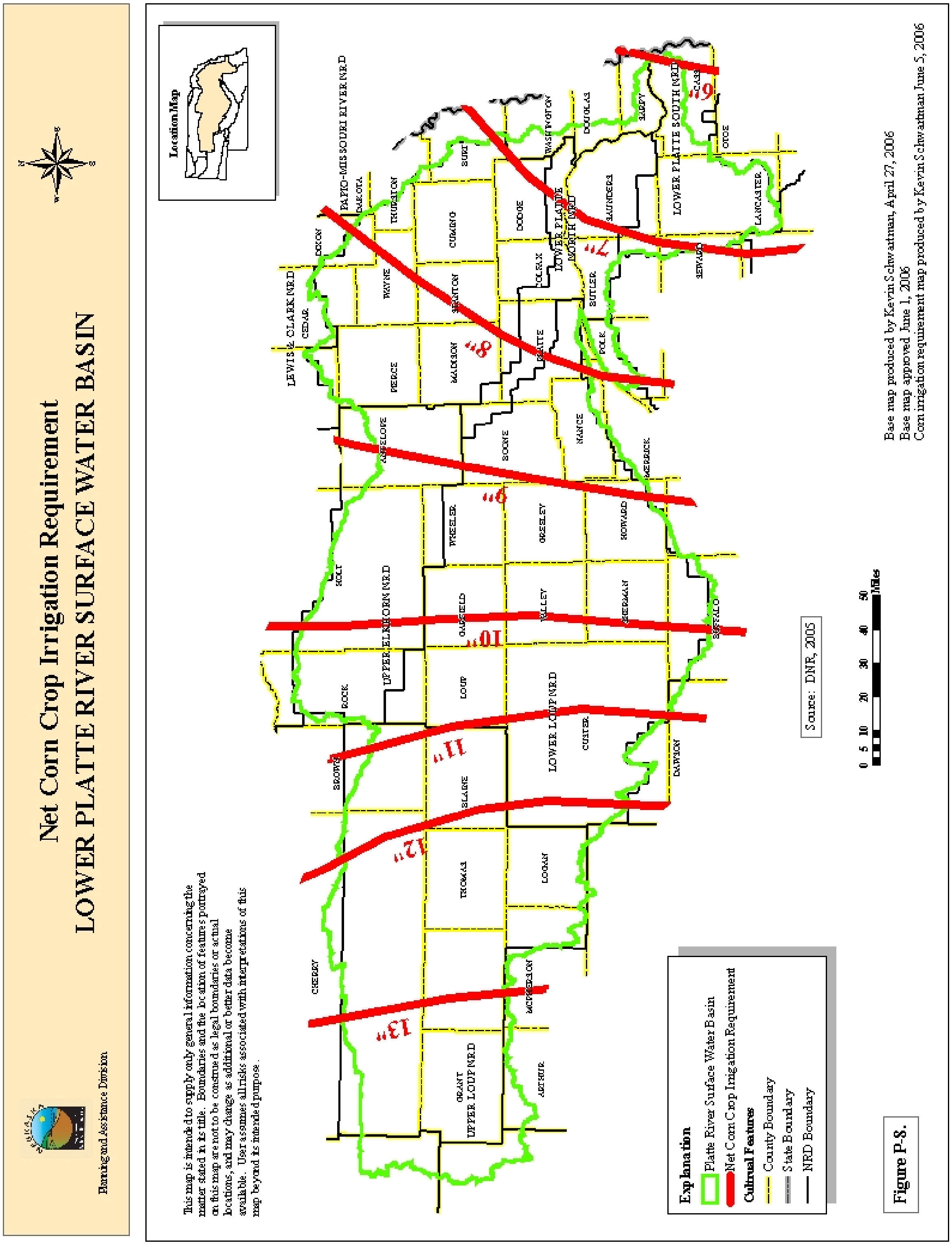
Figure P-7. 10/50 Area, Lower Platte River Basin.



Net Corn Crop Irrigation Requirement

Figure P-8 is a map of the net corn crop irrigation requirement for the Lower Platte River Basin (DNR 2005). The greatest net corn crop irrigation requirement of a junior surface water appropriation above the North Bend gage is 11.7 inches. Assuming a surface water diversion rate equal to 1 cubic foot per second (cfs) per 70 acres, a downtime value of 10 percent, and an efficiency of 80% it will take the most junior surface water appropriation in the reach above North Bend 31.1 days annually to divert 65% of the net corn crop irrigation requirement and 40.6 days to divert 85% of the net corn crop irrigation requirement.

Figure P-8. Net Corn Crop Irrigation Requirement, Lower Platte River Basin.



Surface Water Closing Records

Tables P-1 and P-2 record all surface water administration that has occurred in the basin above the North Bend gage and above the Louisville gage between 1986 and 2005.

Table P-1. Surface Water Administration in the Lower Platte River Basin above the North Bend Gage 1986-2005.

Year	Water Body	Days	Closing Date	Opening Date
2000	Lower Platte River Basin above North Bend	53	Aug 8	Sep 30
2001	Lower Platte River Basin above North Bend	11	Aug 7	Aug 18
2002	Lower Platte River Basin above North Bend	6	Jun 6	Jun 12
2002	Lower Platte River Basin above North Bend	67	Jun 25	Aug 31
2002	Lower Platte River Basin above North Bend	24	Sep 6	Sep 30
2003	Lower Platte River Basin above North Bend	81	Jul 11	Sep 30
2004	Lower Platte River Basin above North Bend	13	May 6	May 19
2004	Lower Platte River Basin above North Bend	7	Jun 29	Jul 6
2004	Lower Platte River Basin above North Bend	58	Jul 27	Sep 23
2005	Lower Platte River Basin above North Bend	48	Jul 12	Aug 29
2005	Lower Platte River Basin above North Bend	28	Sep 2	Sep 30

Table P-2. Surface Water Administration in the Lower Platte River Basin above the Louisville Gage 1986-2005.

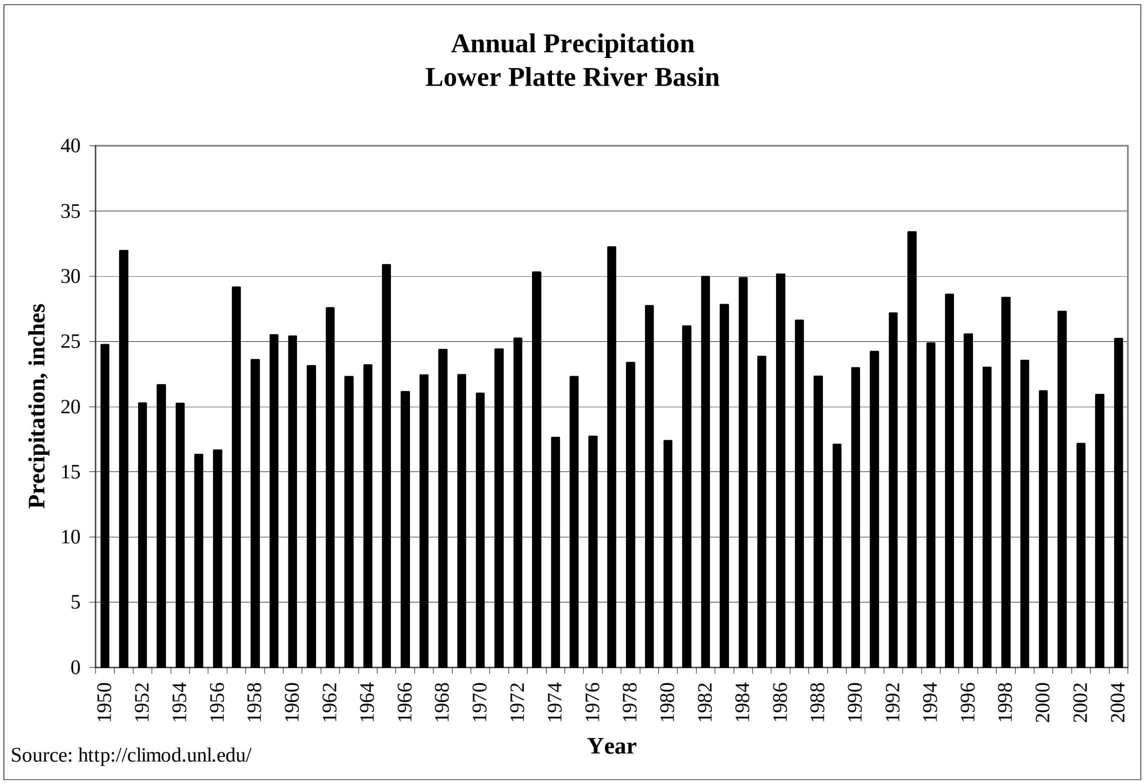
Year	Water Body	Days	Closing Date	Opening Date
1990	Willow Creek	14	Aug 17	Aug 31
1991	Taylor Creek	4	Jul 30	Aug 3
1991	Taylor Creek	3	Aug 23	Aug 26
1991	Taylor Creek	7	Aug 28	Sep 4
1991	Union Creek	7	Aug 28	Sep 4
2000	Lower Platte River Basin above Louisville	53	Aug 8	Sep 30
2001	Lower Platte River Basin above Louisville	11	Aug 7	Aug 18
2002	Lower Platte River Basin above Louisville	6	Jun 6	Jun 12
2002	Lower Platte River Basin above Louisville	59	Jun 25	Aug 23
2002	Lower Platte River Basin above Louisville	4	Aug 27	Aug 31
2002	Lower Platte River Basin above Louisville	24	Sep 6	Sep 30
2003	Lower Platte River Basin above Louisville	66	Jul 14	Sep 18
2004	Lower Platte River Basin above Louisville	13	May 6	May 19
2004	Lower Platte River Basin above Louisville	7	Jun 29	Jul 6
2004	Lower Platte River Basin above Louisville	58	Jul 27	Sep 23
2005	Lower Platte River Basin above Louisville	14	Jul 12	Jul 26
2005	Lower Platte River Basin above Louisville	31	Jul 29	Aug 29
2005	Lower Platte River Basin above Louisville	28	Sep 2	Sep 30

Long-Term Surface Water Supply Evaluation

Future Water Supply

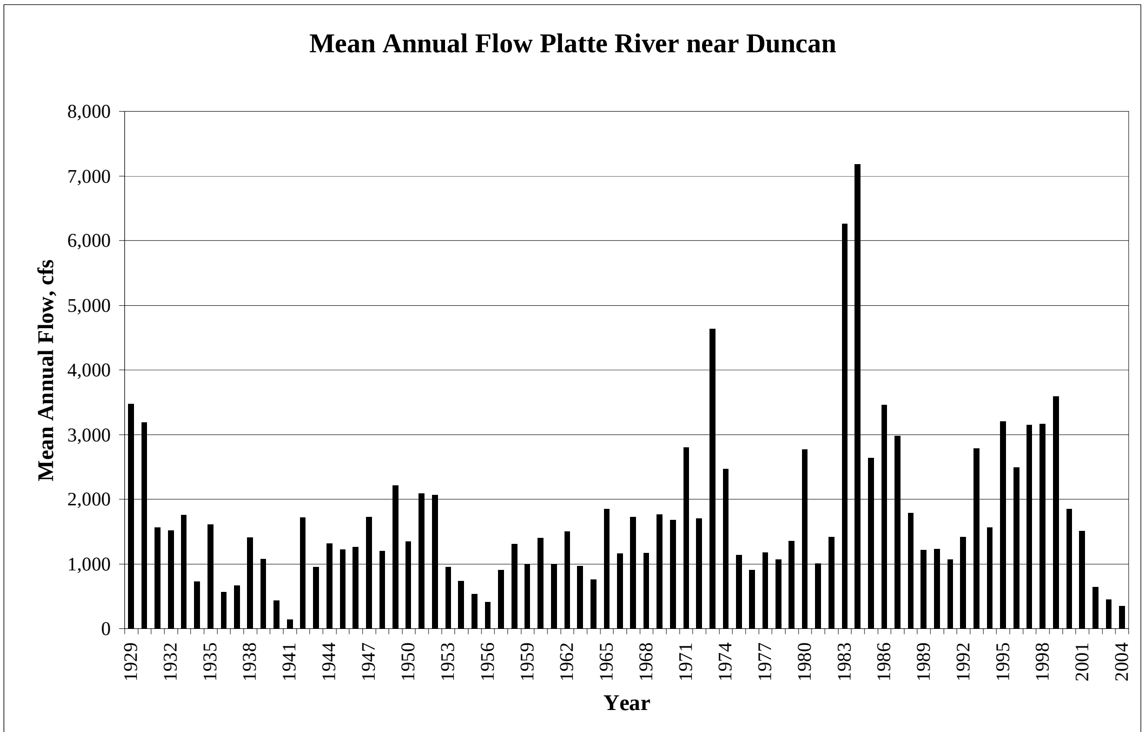
In order to complete the long-term evaluation of surface water supplies, a future 20-year water supply for the basin must be estimated. The basin's major water sources are precipitation, which runs off as direct streamflow and infiltrates into the ground and discharges as baseflow, ground water movement into the basin, which discharges as baseflow, and streamflow from the middle Platte River. Using methodology published in the Journal of Hydrology (Wen and Chen 2005), a nonparametric Mann-Kendall trend test of the weighted average precipitation in the basin was completed. The analysis showed no statistically significant trend in precipitation ($P > 0.95$) over the past 50 years, Figure P-9. The same type of statistical analysis of the streamflows from the middle Platte River, for the Platte River at Duncan (inflow to the Lower Platte Basin), also show no statistically significant trend ($P > 0.95$), Figure P-10. Therefore using the previous 20 years of precipitation and streamflow data as the best estimate of the future surface water supply is a reasonable starting point for applying the lag depletions from ground water wells.

Figure P-9. Annual Precipitation, Lower Platte River Basin[1].



[1] The results include precipitation stations covering the Loup, Elkhorn, and Platte Rivers.

Figure P-10. Mean Annual Flow, Platte River near Duncan.



Source: http://www.usgs.gov/

Depletions Analysis

The future depletions that could be expected due to current well development affecting streamflow in the basin were estimated using SDF methodology as documented in the methodology section. The results estimate the future streamflow at North Bend to be depleted by 185 cfs in 25 years. The results estimate the future streamflow at Louisville to be depleted by 420 cfs in 25 years. The future depletion at Louisville includes 160 cfs from the Metropolitan Utilities District wellfield being developed upstream of the confluence of the Platte and Elkhorn Rivers.

Irrigation Surface Water Appropriation Analysis

The estimates of the 20-year average days available for diversion in 2031 are calculated by comparing the depleted future water supply with the flows necessary to satisfy the senior surface water appropriation (instream flow right) that has caused administration of junior appropriations in the basin. The results of the analyses are shown in Tables P-3 and P-4. The results of the analyses as compared to the numbers of days surface water is required to be available to divert 65% and 85% of the net corn crop irrigation requirement are detailed in Tables P-5 and P-6. In all cases the long-term surface water supply estimate given current levels of development is sufficient to meet the needs of the irrigation surface water supplies.

Table P-3. Estimate of Days Surface Water is Available for Diversion above North Bend.
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Year	July 1 though August 31 Number of Days Surface Water is Available for Diversion	May 1 through September 30 Number of Days Surface Water is Available for Diversion
2012	58	149
2013	41	132
2014	6	63
2015	14	45
2016	14	75
2017	3	63
2018	60	146
2019	62	153
2020	50	131
2021	49	129
2022	61	152
2023	38	129
2024	61	150
2025	61	152
2026	25	86
2027	19	93
2028	1	43
2029	4	70
2030	16	65
2031	6	67
Average	32.5	104.7

Table P-4. Estimate of Days Surface Water is Available for Diversion above Louisville.

Year	July 1 though August 31 Number of Days Surface Water is Available for Diversion	May 1 through September 30 Number of Days Surface Water is Available for Diversion
2012	58	149
2013	42	133
2014	6	63
2015	14	46
2016	16	77
2017	7	68
2018	60	147
2019	62	153
2020	53	141
2021	52	140
2022	61	152
2023	42	133
2024	62	151
2025	62	153
2026	31	92
2027	27	102
2028	4	46
2029	8	74
2030	17	66
2031	7	68
Average	34.6	107.7

Table P-5. Comparison between the Number of Days Required to Meet the Net Corn Crop Irrigation Requirement and Number of Days Surface Water is Available for Diversion above North Bend.

	Number of Days Necessary to Meet the 65% and 85% of Net Corn Crop Irrigation Requirement	**Average Number of Days Available for Diversion at Current Development with 25 Years of Lag Impacts**
July 1 – August 31 (65% Requirement)	31.1	32.5 (1.4 days above the requirement)
May 1 – September 30 (85% Requirement)	40.6	104.7 (64.1 days above the requirement)

Table P-6. Comparison between the Number of Days Required to Meet the Net Corn Crop Irrigation Requirement and Number of Days Surface Water is Available for Diversion above Louisville.

	Number of Days Necessary to Meet the 65% and 85% of Net Corn Crop Irrigation Requirement	**Average Number of Days Available for Diversion at Current Development with 25 Years of Lag Impacts**
July 1 – August 31 (65% Requirement)	31.1	34.6 (3.5 days above the requirement)
May 1 – September 30 (85% Requirement)	40.6	107.7 (67.1 days above the requirement)

Instream Flow Surface Water Appropriation Analysis

During the non-irrigation season, the junior water rights in the Lower Platte River system are the Nebraska Game and Parks Commission's instream flow rights. The purpose of these rights is to maintain habitat for the fish community. Therefore, the Department determined that an appropriate standard of interference would be to determine if the instream flow requirements that could be met at the time the water rights were granted can still be met today. The future surface water supply given the current level of development for instream flow surface water appropriations in the basin were evaluated by applying the same analysis as was done under the erosion rule for irrigation rights on a monthly basis. The 20-year estimate of the future average number of days when the instream flow appropriation would be met at the time of the appropriation application was compared to the 20-year average estimate of the number of days when the instream flow appropriations would be met using the future depleted surface water supply. The results are shown in Table P-7 and P-8. Results show that the Louisville instream flow appropriation has not been eroded and that the North Bend instream flow appropriation has been eroded for the month of January. However, further evaluation of the stream flows at the North Bend gage showed that there were three years in the record in which every January flow value on the recored was not an actual flow measurement but was merely an estimate due to poor stream gaging conditions at the gage. For all other months and years, actual flow values were used. When those three years are removed from the analysis, there are no months with a significant erosion of the 20-year average number of days when the instream flow appropriation was met. The long-term surface water supply estimate in the basin is as sufficient for the instream flow appropriations in the basin as it was at the time of the appropriation date on the permit assuming the current level of development.

Table P-7. Number of Days North Bend Instream Flow Appropriation Expected to be Met

Month	Number of Days Flows Met at Time of Application [1]	Number of Days Flows Met With Current Development [2]
October	26.5	29.7
November	28.6	29.1
December	26.8	26.7
January	28.4	25.8
February	27.2	26.4
March	31.0	30.6
April	30.0	29.9
May	30.5	30.2
June	26.7	28.4
July	17.9	21.3
August	16.3	17.5
September	18.0	21.3

Table P-8. Number of Days Louisville Instream Flow Appropriation Expected to be Met

Month	Number of Days Flows Met at Time of Application [1]	Number of Days Flows Met With Current Development [2]
October	16.9	21.0
November	22.5	24.3
December	20.8	23.7
January	23.4	25.1
February	24.3	24.9
March	30.8	30.3
April	28.7	29.1
May	27.9	28.5
June	23.6	26.7
July	14.8	20.1
August	13.6	14.7
September	15.3	18.3

[1] The number of days instream flows would be expected to be met at the time of application with lag effects of well development at the time of the appropriation

[2] The number of days instream flows would be expected to be met at current time with lag effects of current well development

Ground Water Recharge Sufficiency

The streamflow is sufficient to sustain over the long term the beneficial uses from wells constructed in aquifers dependent on recharge from the stream (Appendix C).

Sufficiency to Avoid Noncompliance with Other State and Federal Laws

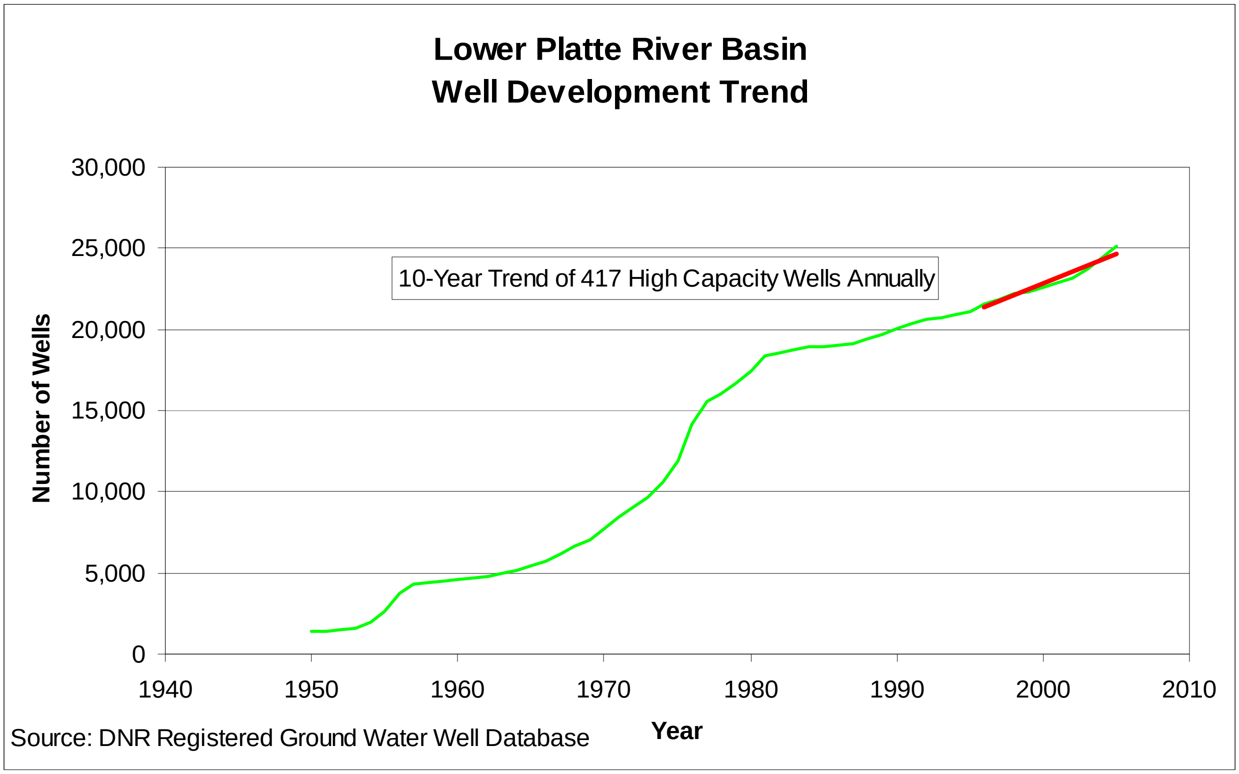
Surface water development in the basin must be in compliance with the Nebraska Non-game and Endangered Species Conservation Act (NNESCA) due to the presence of Pallid Sturgeon and Sturgeon Chub in the Lower Platte River. The Department and the Nebraska Game and Parks Commission have a policy regarding the procedure for issuing new surface water appropriations and amending existing appropriations for compliance with NNESCA. This policy limits the number of surface water appropriations that can be issued without further study of the effects on these species. At this time there is sufficient water supply in the basin to comply with NNESCA. Because future development will be limited so as to continue compliance with NNESCA, the long-term surface water supply in the basin is sufficient.

Future Development

Estimates of the number of high capacity wells (wells pumping greater than 50 gallons per minute) that would be completed over the next 25 years if no new legal constraints on the construction of such wells were imposed were calculated based on extrapolating the present day rate of increase in well development into the future, Figure P-11. For the past 10 years, the rate of increase in high capacity wells is estimated to be 417 wells per year. At the present time, the Lower Loup Natural

Resources District has a two-year moratorium on well development. Therefore, the 10-year rate of development of high capacity wells for the Lower Loup Natural Resources District, 134 wells per year, were not included for 2007 and 2008, but the rate of 134 wells per year was included for the years 2009 through 2032.

Figure P-11. High Capacity Well Development, Lower Platte River Basin.



The future depletions that could be expected due to current and future well development affecting streamflow in the basin were estimated using SDF methodology. The results estimate the future streamflow at North Bend to be depleted by 325 cfs in 10 years, 480 cfs in 15 years, 630 cfs in 20 years and 775 cfs in 25 years. The results estimate the future streamflow at Louisville to be depleted by 620 cfs in 10 years, 835 cfs in 15 years, 1,040 cfs in 20 years, and 1,240 cfs in 25 years. The future depletion at Louisville includes 160 cfs of depletion from the Metropolitan Utilities District wellfield located upstream of the confluence of the Elkhorn and Platte Rivers[2].

The estimate of the 20-year average number of days surface water is available for diversion in 2031 with additional future development are calculated by comparing the depleted future water

[2] This is water that is pumped from the stream by the wellfield, not the water the permit calls for as an instream flow.

supply with the flows necessary to satisfy the senior surface water appropriation. The results of the analyses are shown in Tables P-9 and P-10. The results of the analyses as compared to the numbers of days surface water is required to be available to divert 65% and 85% of the net corn crop irrigation requirement are detailed in Tables P-11 and P-12. The results indicate that the Department's conclusion that the basin is not fully appropriated would change to a preliminary determination that the basin is fully appropriated if there are no additional constraints on future development of surface water and ground water in the basin based on current information.

Table P-9. Estimated Number of Days Surface Water is Available for Diversion above North Bend with Future Development.

Year	July 1 though August 31 Number of Days Surface Water is Available for Diversion	May 1 through September 30 Number of Days Surface Water is Available for Diversion
2012	55	145
2013	36	126
2014	4	54
2015	13	40
2016	10	71
2017	2	61
2018	55	127
2019	62	152
2020	46	116
2021	46	119
2022	54	144
2023	36	126
2024	59	137
2025	54	144
2026	13	67
2027	4	66
2028	0	28
2029	1	55
2030	13	44
2031	2	56
Average	28.3	93.9

Table P-10. Estimated Number of Days Surface Water is Available for Diversion above Louisville with Future Development.

Year	July 1 though August 31 Number of Days Surface Water is Available for Diversion	May 1 through September 30 Number of Days Surface Water is Available for Diversion
2012	56	146
2013	37	127
2014	4	54
2015	13	41
2016	12	73
2017	5	64
2018	55	128
2019	62	152
2020	48	131
2021	48	128
2022	55	145
2023	39	129
2024	61	139
2025	62	152
2026	20	77
2027	11	78
2028	3	33
2029	3	60
2030	15	50
2031	3	61
Average	30.6	98.4

Table P-11. Comparison between the Number of Days Required to Meet the Net Corn Crop Irrigation Requirement and Number of Days Surface Water is Available for Diversion above North Bend with Future Development.

	Number of Days Necessary to Meet the 65% and 85% of Net Corn Crop Irrigation Requirement	**Average Number of Days Available for Diversion with Future Development and 25 Years of Lag Impacts**
July 1 – August 31 (65% Requirement)	31.1	28.3 (2.8 days below the requirement)
May 1 – September 30 (85% Requirement)	40.6	94.5 (53.9 days above the requirement)

Table P-12. Comparison between the Number of Days Required to Meet the Net Corn Crop Irrigation Requirement and Number of Days Surface Water is Available for Diversion above Louisville with Future Development.

	Number of Days Necessary to Meet the 65% and 85% of Net Corn Crop Irrigation Requirement	**Average Number of Days Available for Diversion with Future Development and 25 Years of Lag Impacts**
July 1 – August 31 (65% Requirement)	31.1	30.6 (0.5 days above the requirement)
May 1 – September 30 (85% Requirement)	40.6	99.0 (58.4 days above the requirement)

Future Analysis

An effort to categorize the aquifer characteristics and the water supply of the glaciated portion of eastern Nebraska which includes large areas of the Lower Platte River Basin is underway. This extensive body of work will provide critical data for use in future reports. It is critical for the Department and others to continue these efforts and studies.

A substantial portion of the Lower Platte River Basin is included in the Elkhorn-Loup ground water model (ELM) which is currently being developed for evaluating the ground water and surface water relationship and water supply of much of the Elkhorn and all of the Loup River Basins. Although not developed to specifically evaluate water supply for the Lower Platte River Basin, this model can be utilized to analyze water resources in the basin. Efforts will be made to incorporate results from this model in future reports.

Conclusions

Based upon available information and its evaluation, the Department has reached a preliminary conclusion that the Lower Platte River Basin is not fully appropriated. The Department has also determined that if no additional legal constraints are imposed on future development of hydrologically connected surface water and ground water and reasonable projections are made about the extent and location of future development, this preliminary conclusion would change to a conclusion that the basin is fully appropriated above the North Bend gage based on current information. There is no estimated date for when the Department will have to conclude that the basin is fully appropriated.

Bibliography of Hydrogeologic References for Lower Platte River Basin

Conservation and Survey Division. 2005. *Mapping of Aquifer Properties-Transmissivity and Specific Yield-for Selected River Basins in Central and Eastern Nebraska.* Lincoln.

Nebraska Department of Natural Resources. 2005. *2006 Annual Evaluation of Availability of Hydrologically Connected Water Supplies*. Lincoln, Nebraska: Department of Natural Resources.

Wen, F.J., and X.H. Chen. 2005. Streamflow trends and depletion study in Nebraska with a focus on the Republican River Basin. *Water Resources Research* (In Review).

Missouri Tributary Basins

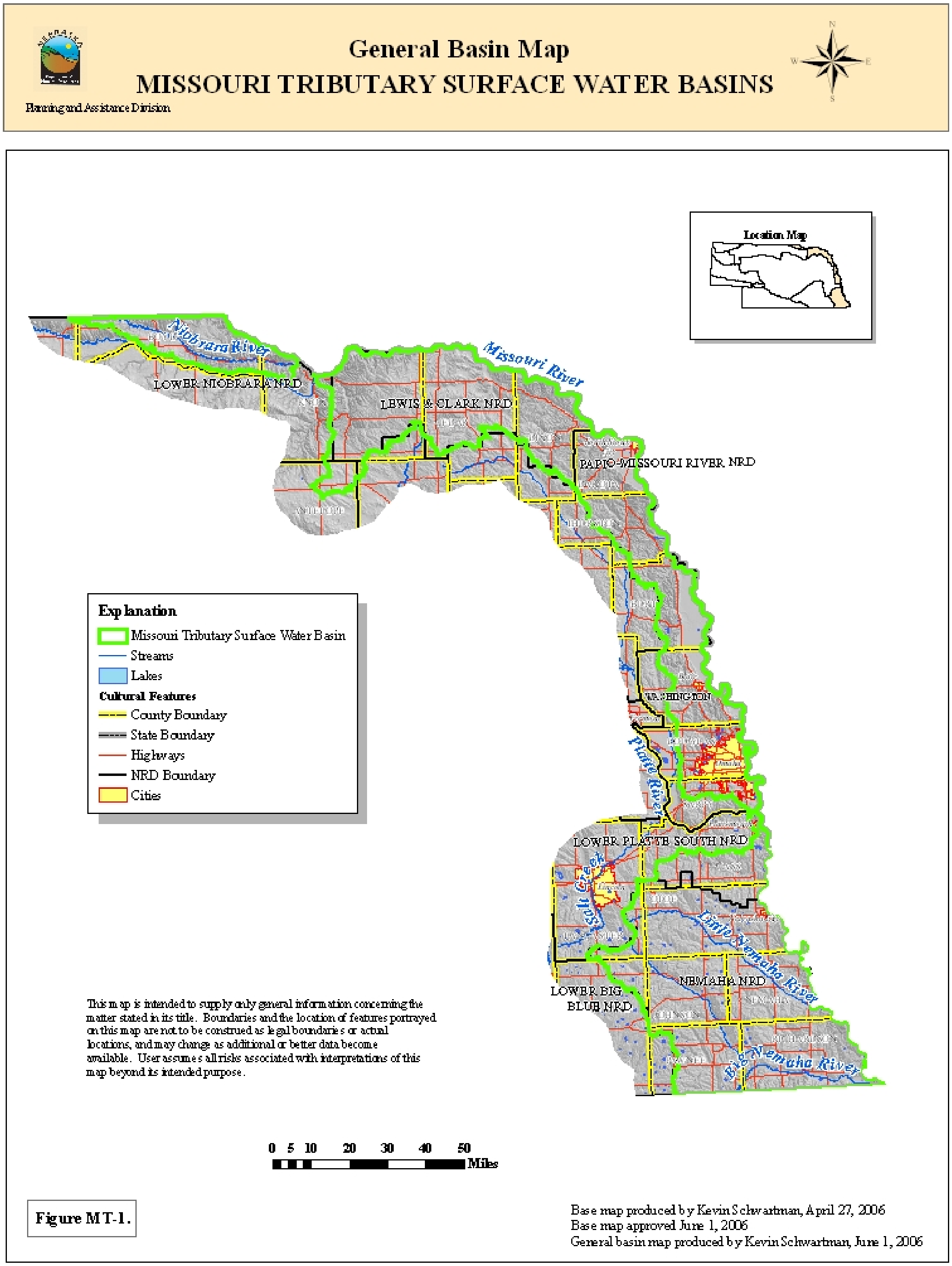
Summary

Based on the analysis of the sufficiency of the long-term surface water supply in the Missouri Tributary basins, the Department has reached a preliminary conclusion that the basins are not fully appropriated. Even though the effects of future ground water development on future water supplies were not estimated in the basins, the current number of days in which surface water was available for diversion far exceeds the number of days necessary to meet the net corn crop irrigation requirement. The best available data does not allow for analysis of whether or not this determination would change if no additional legal constraints are imposed on future development.

Basin Descriptions

The Missouri Tributary basins include all surface areas that drain directly into the Missouri River with the exceptions of the Niobrara River and Platte River basins, Figure M-1, and all areas of ground water which impact surface water flows of the basins. Specific streams in these basins include Ponca Creek, Bazile Creek, Weeping Water Creek, the Little Nemaha River, and the Big Nemaha River. The total area of the Missouri Tributaries surface water basins is approximately 6,200 square miles of which approximately 450 square miles drain into the Missouri River above the Niobrara River confluence, approximately 3,000 square miles drain into the Missouri River between the Niobrara River confluence and the Platte River confluence, and 2,800 square miles drain into the Missouri River below the Platte River confluence. Natural Resources Districts with significant areas in the basins are the Lower Niobrara Natural Resources District, the Lewis and Clark Natural Resources District, the Papio-Missouri River Natural Resources District, and the Nemaha Natural Resources District.

Figure MT-1. General Basin Map, Missouri Tributary Basins.



Nature and Extent of Water Use

Ground Water

Ground water in the basins is used for a variety of purposes: domestic, industrial, livestock, irrigation, and other uses. There are a total of 5,533 registered ground water wells within the basins as of December 31, 2005 (Department registered ground water wells database), with an estimated 300 ground water wells to be developed during 2006, Figure M-2. The locations of all active ground water wells can be seen in Figure M-3.

Figure MT-2. Current Well Development by Number of Registered Wells, Missouri Tributary Basins.

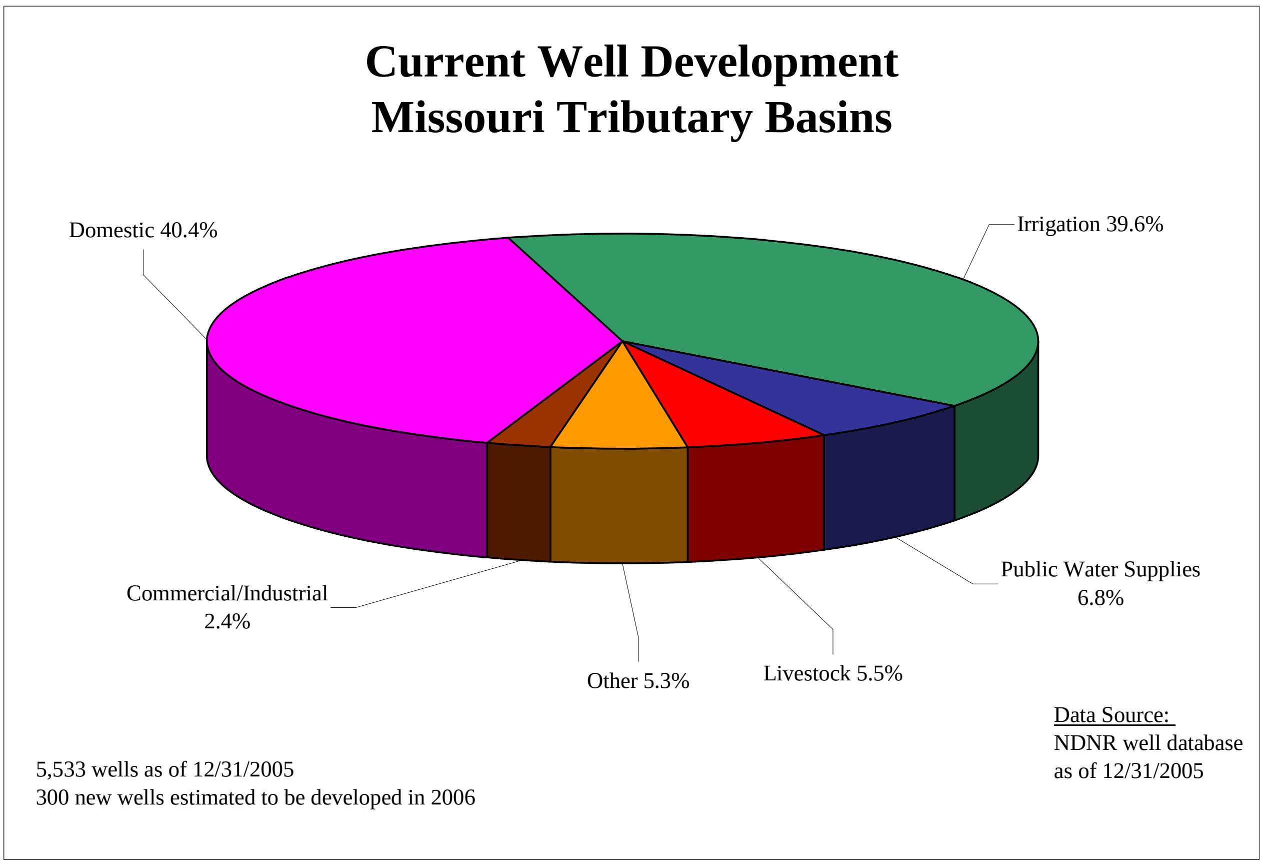
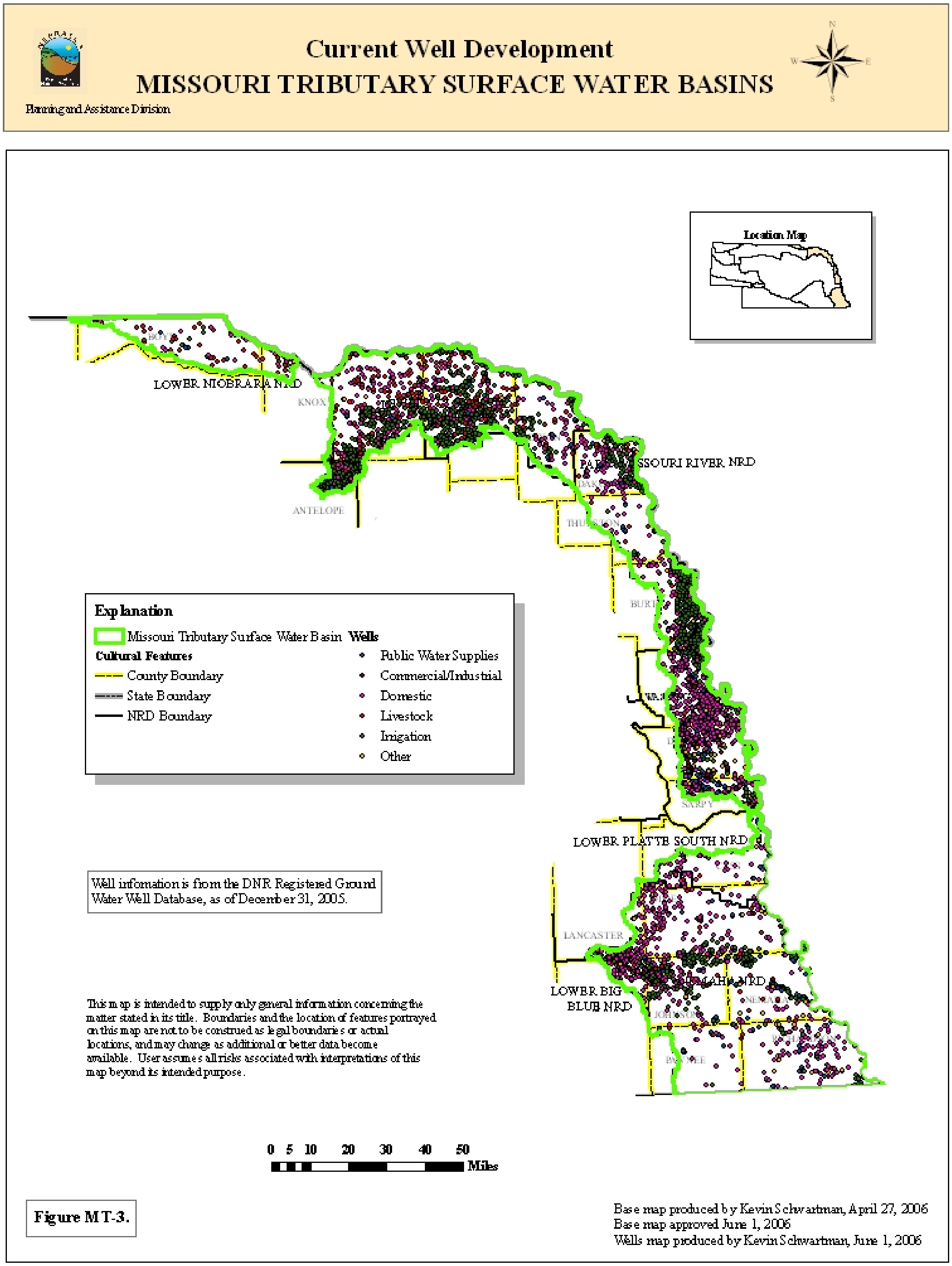


Figure MT-3. Current Well Locations, Missouri Tributary Basins.



Surface Water

As of December 31, 2005, there were 1,369 surface water appropriations in the basins issued for a variety of uses, Figure M-4. The majority of the surface water appropriations are for storage and irrigation use and tend to be located on the major streams. The first surface water appropriations in the basins were permitted in 1881 and development has continued through present day. The approximate locations of the surface water diversions are shown in Figure M-5.

Figure MT-4. Surface Water Appropriations by Number of Diversion Points, Missouri Tributary Basins.

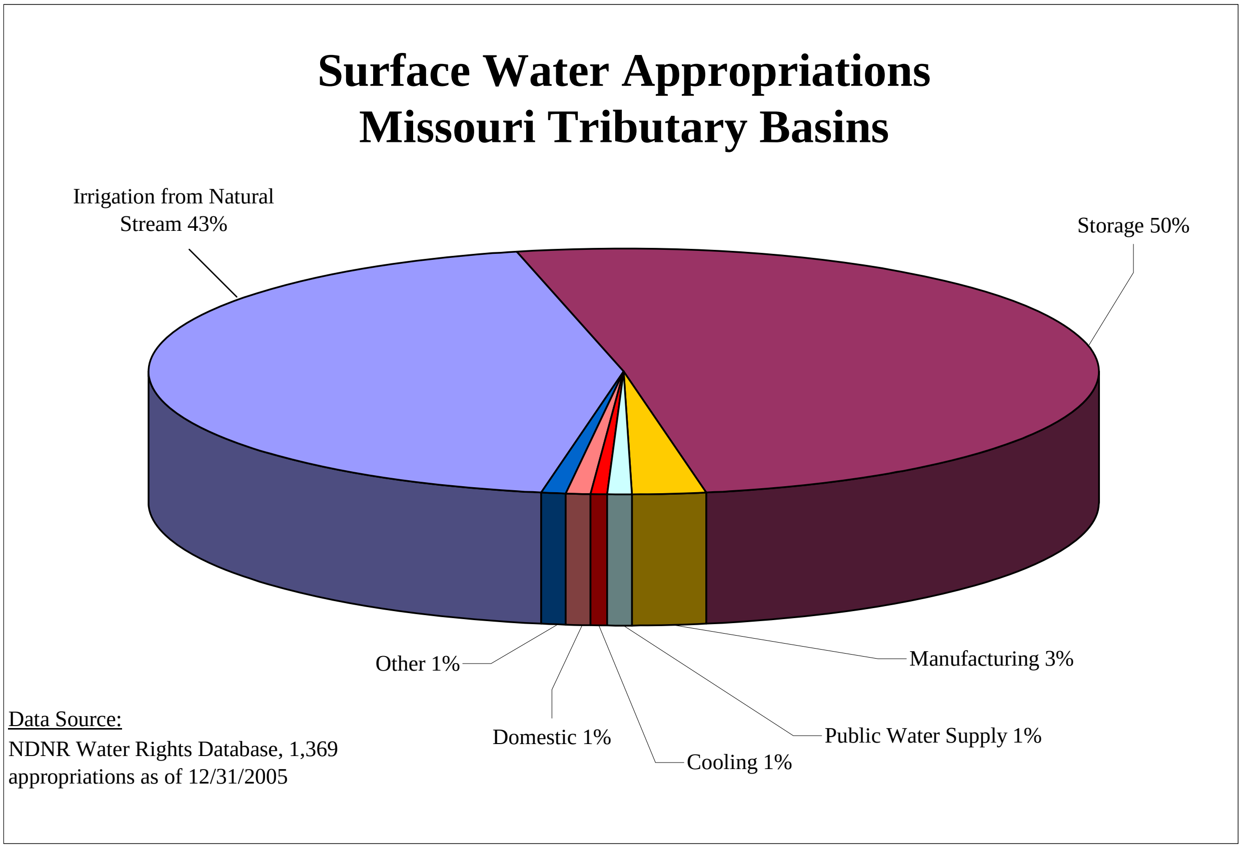
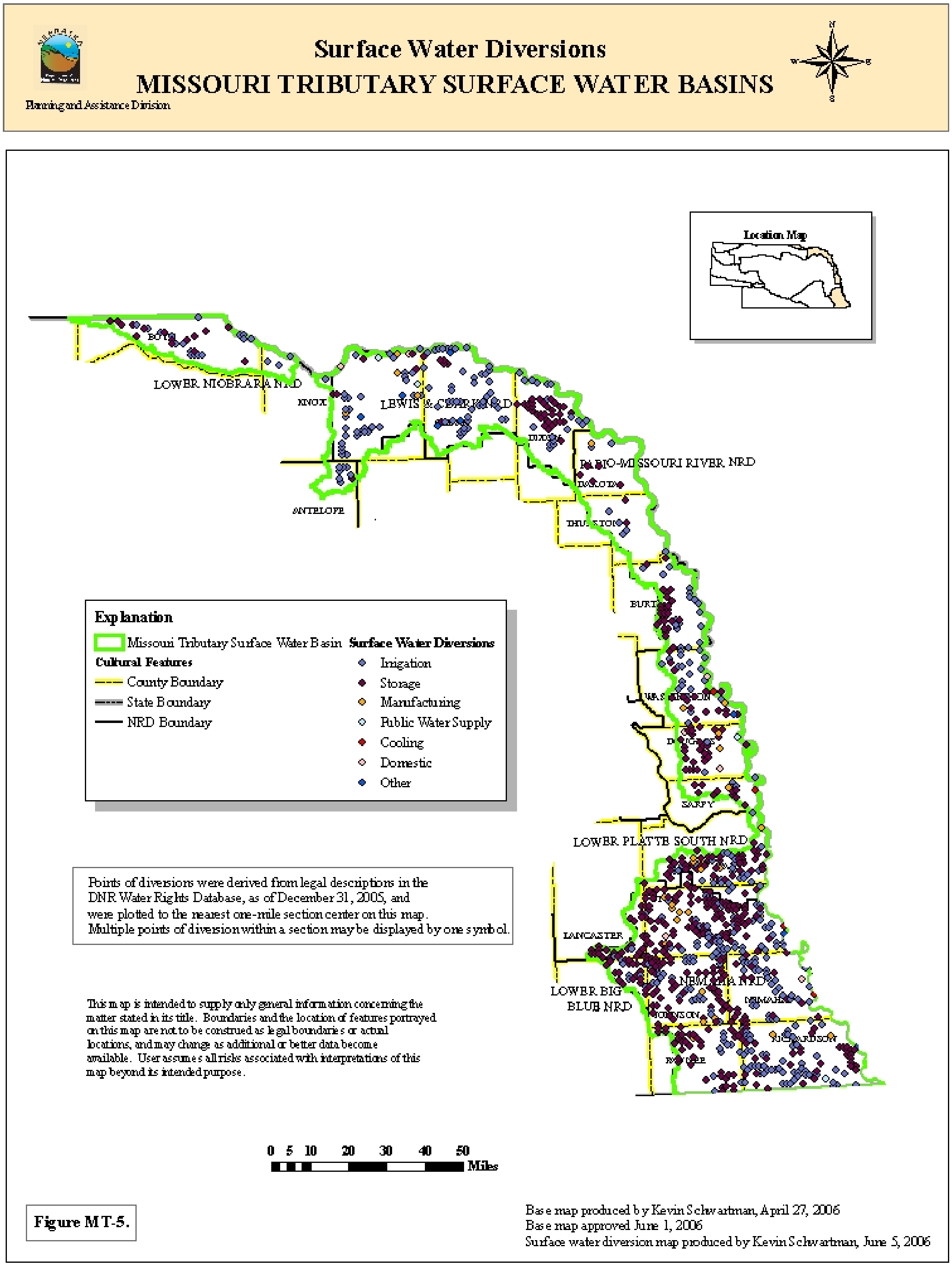


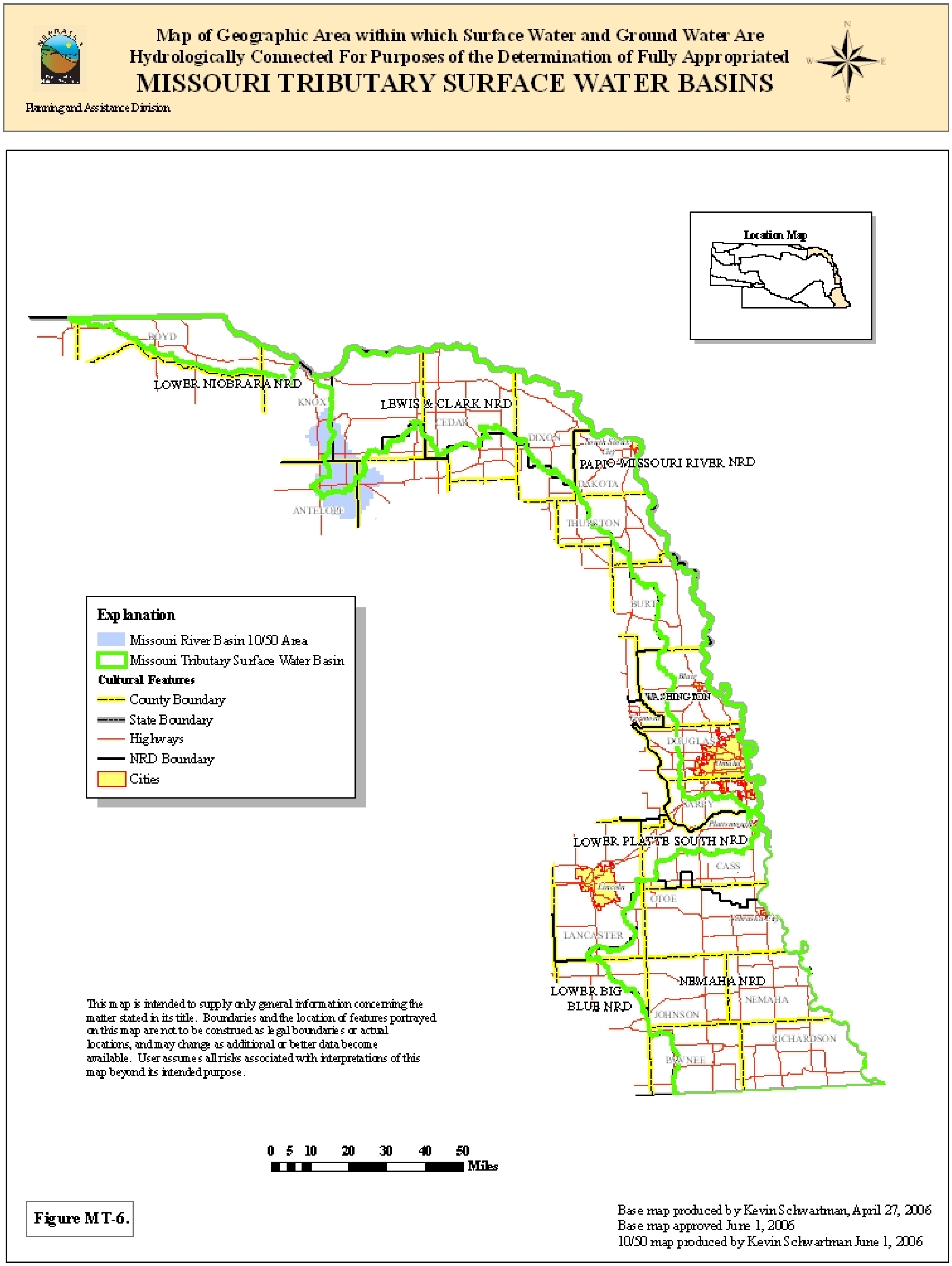
Figure MT-5. Surface Water Appropriation Diversion Locations, Missouri Tributary Basins.



Hydrologically Connected Area

No sufficient numeric ground water model is available in the Missouri Tributary basins to determine the 10 percent depletion in 50-year area (10/50 area). The stream depletion factor (SDF) methodology can only be applied where sufficient data and appropriate hydrogeologic conditions exist. In most of the basins the principal aquifer is absent or very thin due to the glaciated nature of the area (CSD 2005). Additionally, where there is a principal aquifer present, the complex hydrogeologic nature of this area makes the degree of connection between the ground water system and the surface water system poor and uncertain (CSD 2005). The area surrounding headwaters of Bazile Creek is the only portion of the basins where the principal aquifer is present and known to be in hydrologic connection with the streams (CSD 2005) and the 10/50 area can be calculated, Figure M-6. A description of the SDF methodology used appears in the methodology section of this report.

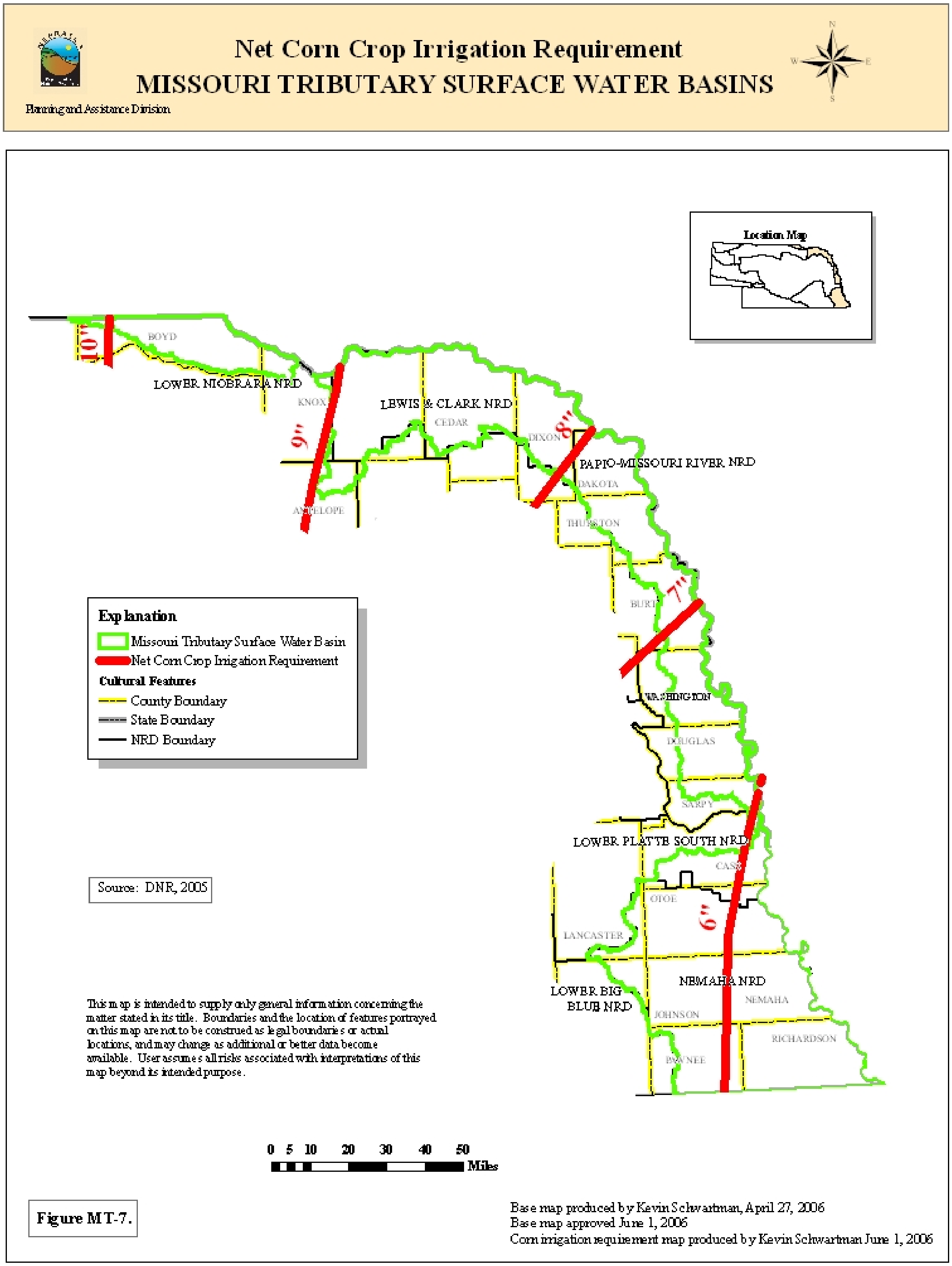
Figure MT-6. 10/50 Area, Missouri Tributary Basins.



Net Corn Crop Irrigation Requirement

Figure M-7 is a map of the net corn crop irrigation requirement for the basins (DNR 2005). The net corn crop irrigation requirement in the basins range from 5.3 to 10.0 inches. Assuming a surface water diversion rate equal to 1 cubic foot per second per 70 acres and a downtime value of 10 percent, it will take between 14.1 and 26.6 days annually to divert 65% of the net corn crop irrigation requirement and between 18.4 and 34.7 days to divert 85% of the net corn crop irrigation requirement.

Figure MT-7. Net Corn Crop Irrigation Requirement, Missouri Tributary Basins.



Surface Water Closing Records

Table M-1 records all surface water administration that has occurred in the basins between 1986 and 2005.

Table MT-1. Surface Water Administration in the Missouri Tributary Basins, 1986-2005.

Year	Water Body	Days	Closing Date	Opening Date
1988	Menominee Creek	???*	Jun 27	
1989	Little Nemaha River	25		
1989	North Fork Big Nemaha River	14		
1989	Long Branch	5		
1990	North Fork Little Nemaha River	14	July	July
1991	Little Nemaha River	7	Jul 2	Jul 9
1991	Little Nemaha River	19	Jul 18	Aug 6
1991	North Fork Little Nemaha River	1	Jul 8	Jul 9
2002	Weeping Water Creek	21	Jul 30	Aug 20
2004	Weeping Water Creek	3	Aug 23	Aug 26
2005	Weeping Water Creek	3	Jul 15	Jul 18

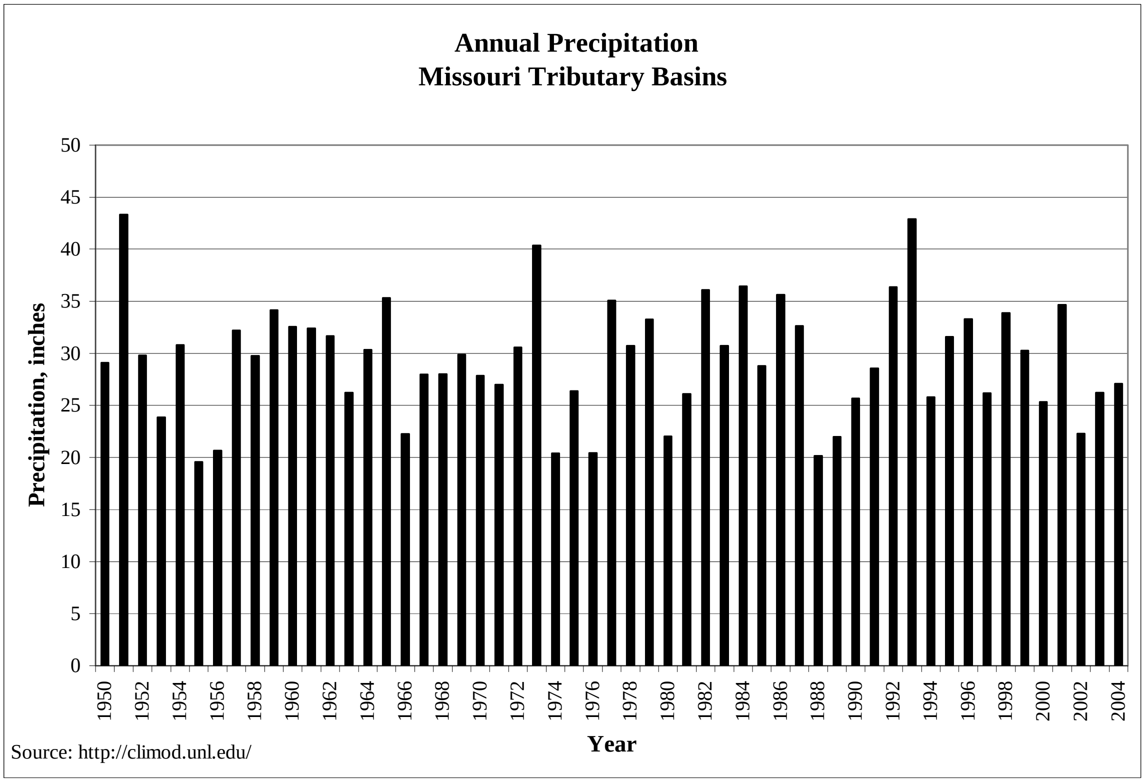
* Ending date could not be determined from administration records.

Long-Term Surface Water Supply Evaluation

Future Water Supply

In order to complete the long-term evaluation of surface water supplies, a future 20-year water supply for the basins must be estimated. The basins' water sources are precipitation which runs off as direct streamflow and infiltrates into the ground which discharges as baseflow and ground water movement into the basin which discharges as baseflow. Using methodology published in the Journal of Hydrology (Wen and Chen 2005), a nonparametic Mann-Kendall trend test of the weighted average precipitation in the basins was completed. The analysis showed no statistically significant trend in precipitation (P > 0.95) over the past 50 years, Figure M-8. Data does not exist to test whether there is a changing trend in ground water movement into the basin. Therefore using the previous 20 years of streamflow data as the best estimate of the future surface water supply is a reasonable starting point for applying the lag depletions from ground water wells.

Figure MT-8. Annual Precipitation, Missouri Tributary Basins.



Depletions Analysis

The future depletions that could be expected due to current well development affecting streamflow in the basins were not estimated for the same reasons as described in the “Hydrologically Connected Area” subsection above.

Irrigation Surface Water Appropriation Analysis

The comparison of the near-term water supply days available for diversion to the number of days surface water is required to be available to divert 65% and 85% of the net corn crop irrigation requirement are detailed in Table M-2. There is no estimate of the 20-year average days available for diversion in 2031 for the basins due to the inadequacy of current data and models in predicting future stream depletions. Even though the future water supplies were not estimated, the current number of days in which surface water was available for diversion far exceeds the number of days necessary to meet the net corn crop irrigation requirement.

Table MT-2. Comparison between the Number of Days Required to Meet the Net Corn Crop Irrigation Requirement and Number of Days Surface Water is Available for Diversion in the Missouri Tributary Basins.

	Number of Days Necessary to Meet the 65% and 85% of Net Corn Crop Irrigation Requirement	**Near-Term Supply Average Number of Days Available for Diversion (1986-2005)**
July 1 – August 31 (65% Requirement)	14.1 to 26.6	59.5 or greater (at least 32.9 days above the requirement)
May 1 – September 30 (85% Requirement)	18.4 to 34.7	150.5 or greater (at least 115.8 days above the requirement)

Ground Water Recharge Sufficiency

The streamflow is not insufficient to sustain over the long term the beneficial uses from wells constructed in aquifers dependent on recharge form the stream (Appendix C).

Sufficiency to Avoid Noncompliance

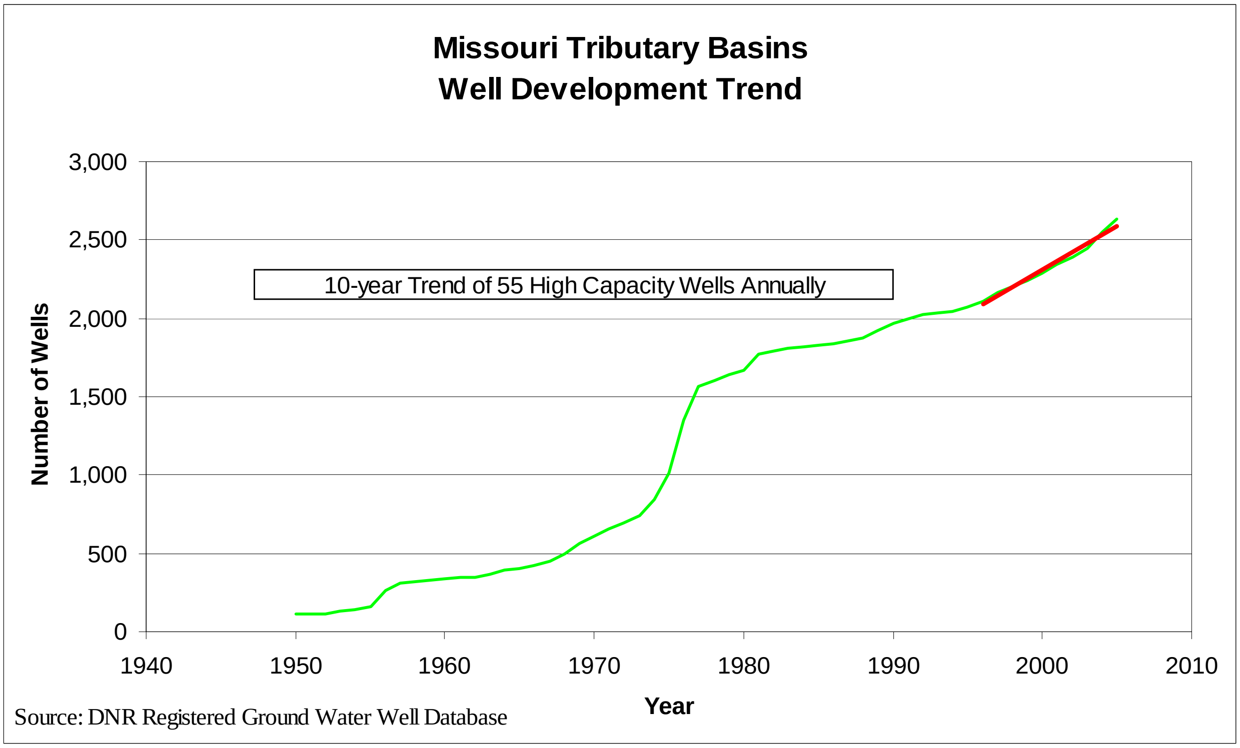
There are no compacts on any portions of the Missouri Tributary basins in Nebraska.

Future Development

Estimates of the number of high capacity wells (wells pumping greater than 50 gallons per minute) that would be completed over the next 25 years if no new legal constraints on the construction of such wells were imposed were calculated based on extrapolating the present day rate of increase in well development into the future, Figure M-9. For the past 10 years, the rate of increase in high capacity wells is linear at a rate of 55 wells per year in the basins.

For reasons the same as stated above in the “Depletions Analysis” subsection of this section, no estimates of depletions due to current and future ground water development were computed. Even though the effects on future water supplies were not estimated, the current number of days in which surface water was available for diversion far exceeds the number of days necessary to meet the net corn crop irrigation requirement.

Figure MT-9. High Capacity Well Development, Missouri Tributary Basins.



Future Analysis

An effort to categorize the aquifer characteristics and the water supply of the glaciated portion of eastern Nebraska, which includes large areas of the Missouri Tributary basins, is underway. This extensive body of work will provide future reports with critical data on the hydrologically connected areas and impacts of future development.

Conclusions

Based upon available information and its evaluation, the Department has reached a preliminary conclusion that the Missouri Tributary basins are not fully appropriated. The best available data does not allow for analysis of whether or not this determination would change if no additional legal constraints are imposed on future development of hydrologically connected surface water and ground water.

Bibliography of Hydrogeologic References for Missouri Tributaries River Basin

Conservation and Survey Division. 2005. *Mapping of Aquifer Properties-Transmissivity and Specific Yield-for Selected River Basins in Central and Eastern Nebraska.* Lincoln.

Nebraska Department of Natural Resources. 2005. *2006 Annual Evaluation of Availability of Hydrologically Connected Water Supplies*. Lincoln, Nebraska: Department of Natural Resources.

Wen, F.J., and X.H. Chen. 2005. Streamflow trends and depletion study in Nebraska with a focus on the Republican River Basin. *Water Resources Research* (In Review).

VI. Basin Summaries and Results

Basin Summaries

Blue River Basins

The Blue River basins are located in south-central Nebraska and consist of all of the surface water areas that drain into the Big Blue River and the Little Blue River and all areas of ground water that impact surface water flows of the basins.

The basins can be divided into two distinct areas based on whether or not they have been glaciated. In areas that have been glaciated, the restrictive and complex nature of the hydrogeology does not allow the use of stream depletion factor (SDF) methodologies. Therefore, the Department was unable to delineate the 10/50 area for the glaciated portions of the basins. The Big Blue River and its tributaries in the non-glaciated areas of the basin are not thought to be in hydrological connection with the aquifers in the area and by definition, no 10/50 area was delineated. In the non-glaciated portions of the Little Blue River Basin, a numerical ground water model was used to delineate the 10/50 area.

The numerical ground water model was not able to provide data on the lag impacts from ground water development so no lag effects were calculated. However, because the Department determined that the near term availability of surface water for diversion for each basin far exceeds the number of days necessary to meet 65% and 85% of the net corn crop irrigation requirement for the rule's applicable time periods in the basins, the Department was able to reach a preliminary conclusion that no portions of the basins are fully appropriated without having to calculate the lag effect from wells in the basin. Because of the inability to calculate the lag effects of existing and future ground water development, the long term surface water availability was not determined. Although reductions in flows may require water administration more often in the future, due to the terms of the Kansas-Nebraska Big Blue River Compact, low flows do not cause noncompliance with the Compact.

Lower Niobrara Basin

The Lower Niobrara River Basin is located in the north-central portion of Nebraska and consists of all of the surface water areas that drain into the Niobrara River that had not previously been determined to be fully appropriated, from the Mirage Flats Diversion Dam to the confluence of the Niobrara River and the Missouri River, and all areas of ground water that impact surface water flows of the basin.

No sufficient numerical ground water model is available in the Lower Niobrara River Basin, therefore the stream depletion factor (SDF) methodology was used to determine the 10/50 area. (See Section IV)

The Department has reached a preliminary conclusion that no portion of the basin is fully appropriated. The near term availability of surface water for diversion far exceeds the number of days necessary to meet 65% and 85% of the net corn crop irrigation requirement for the rule's applicable time periods in the basin and has not eroded instream flow appropriations in the basin. Because of the inability to quantify the estimated lag effects of existing and future ground water development, the long term surface water availability was not determined.

Lower Platte River Basin

The Lower Platte River Basin is located in the central and eastern portions of Nebraska and consists of all the surface water areas that drain into the Platte River from its confluence with the Loup River to its confluence with the Missouri River, including those areas that drain into the Loup River and the Elkhorn River and all areas of ground water that impact surface water flows of the basin.

No sufficient numerical ground water model is available in the Lower Platte River Basin so SDF methodology was used to determine the 10/50 area. (See Section IV)

The Department has reached a preliminary conclusion that no portion of the basin is fully appropriated. The long term availability of surface water for diversion exceeds the number of days necessary to meet 65% and 85% of the net corn crop irrigation requirement for the rule's applicable time periods in the basins and has not eroded instream flow appropriations in the basin (the junior right administered for in the non-irrigation season). However, based on reasonable projections of the extent and location of future development in the basin, the analysis also shows that this preliminary conclusion would change to be fully appropriated in the subbasin of the Platte River Basin above the North Bend gage if no additional constraints were placed on future surface water and ground water development.

Missouri Tributary Basins

The Missouri Tributary basins are located in the north-central and eastern portions of Nebraska and consist of all of the surface water areas that drain directly into the Missouri River with the exceptions of the Niobrara River and Platte River basins and all areas of ground water which impact surface water flows of the basins.

No sufficient numerical ground water model is available in the Missouri Tributary basins to determine the 10/50 area. Much of the basins have been glaciated and in those areas that have been glaciated, the restrictive and complex nature of the hydrogeology does not allow the use of existing methodologies. Therefore the Department was unable to delineate the 10/50 area for the glaciated portions of the basins. The non-glaciated area surrounding the headwaters of Bazile Creek is the only portion of the basins where the principal aquifer is present and in hydrologic connection with the streams and, therefore, the 10/50 area was delineated using SDF methodology. (See Section IV)

The Department has reached a preliminary conclusion that no portions of the basins are fully appropriated. The near term availability of surface water for diversion far exceeds the number of days necessary to meet 65% and 85% of the net corn crop irrigation requirement for the rule's applicable time periods in the basins. Because of the inability to calculate the lag effects of existing and future ground water development, the long term surface water availability was not determined.

Results of Analyses

Tables 1 and 2 summarize the results of the analysis for sufficiency of water availability for irrigation in each basin. These results show that during the period of July 1 through August 31 that water is most likely to be insufficient to meet the standard for determining a basin is fully appropriated. The subbasin closest to failing to meet the standard is the Lower Platte River Basin above North Bend.

Table BS-1. Summary of Comparison between the Number of Days Required to Meet 65% of the Net Corn Crop Irrigation Requirement and Number of Days in which Surface Water is Available for Diversion (July 1 – August 31).

	Days Necessary to Meet 65% of Net Corn Crop Irrigation Requirement	Average Number of Days Available for Diversion at Current Development with 25 Years of Lag Impacts	Average Number of Days Available for Diversion with Future Development and 25 Years of Lag Impacts
Big Blue River Basin	23.9	56.1*	Not Calculated**
Little Blue River Basin	25.7	54.4*	Not Calculated**
Lower Platte River Basin above North Bend including the Loup River Basin	31.1	32.5	28.3
Lower Platte River Basin above Louisville including the Elkhorn River Basin	31.1	34.6	30.6
Lower Niobrara River Basin	23.6 – 36.9	61.9 or greater*	Not Calculated**
Missouri Tributary Basins	14.1 – 26.6	59.5 or greater*	Not Calculated**

* This number is the near-term average number of days in which surface water is available for diversion (1986 – 2005).

** This number was not estimated because the near term average number of days in which surface water is available for diversion so far exceeds the number of days necessary to meet the net corn crop irrigation requirement.

Table BS-2. Summary of Comparison between the Number of Days Required to Meet 85% of the Net Corn Crop Irrigation Requirement and Number of Days in which Surface Water is Available for Diversion (May 1 – September 30).

	Number of Days Necessary to Meet 85% of Net Corn Crop Irrigation Requirement	Average Number of Days Available for Diversion at Current Development with 25 Years of Lag Impacts	Average Number of Days Available for Diversion with Future Development and 25 Years of Lag Impacts
Big Blue River Basin	31.3	147.1*	Not Calculated**
Little Blue River Basin	33.6	142.5*	Not Calculated**
Lower Platte River Basin above North Bend including the Loup River Basin	40.6	104.7	94.5
Lower Platte River Basin above Louisville including the Elkhorn River Basin	40.6	107.7	99.0
Lower Niobrara River Basin	30.9 – 48.3	152.9 or greater*	Not Calculated**
Missouri Tributary Basins	18.4 – 34.7	150.5 or greater*	Not Calculated**

* This number is the near-term average number of days in which surface water is available for diversion (1986 – 2005).

** This number was not estimated because the near term average number of days in which surface water is available for diversion so far exceeds the number of days necessary to meet the net corn crop irrigation requirement.

Appendix A

NOTICE TO PUBLIC

RELATING TO ANNUAL REPORT REQUIRED PURSUANT TO Neb. Rev. Stat. § 46-713

The Nebraska Department of Natural Resources ("Department") hereby provides notice that the Department, in accordance with Section 46-713(1)(c), shall include in the annual report required to be issued by January 1 of 2007, for informational purposes only, a summary of relevant data provided by any interested party concerning the social, economic, and environmental impacts of additional hydrologically connected surface water and ground water uses on resources that are dependent on streamflow or ground water levels but are not protected by appropriations or regulations. Anyone wishing to provide relevant data must submit such relevant data by April 1, 2006, to the Department. The address for the Department of Natural Resources is 301 Centennial Mall South, P.O. Box 94676, Lincoln, Nebraska, 68509-4676, Attention: Tina Kurtz. FAX: (402) 471-2900.

The Department must complete an evaluation of the expected long-term availability of hydrologically connected water supplies for both existing and new surface water uses and existing and new ground water uses in each of the state's river basins and shall issue a report that describes the results of the evaluation by January 1, 2007, pursuant to Neb. Rev. Stat. § 46-713 (Reissue 2004). Based on the information reviewed in the evaluation process, the Department shall arrive at a preliminary conclusion for each river basin, subbasin, and reach evaluated as to whether such river basin, subbasin, or reach presently is fully appropriated without the initiation of additional uses.

For further information regarding the Department, and its activities, please refer to the Department's web site, at http://www.dnr.state.ne.us.

PROOF OF PUBLICATION

AFFIDAVIT

State of Nebraska, County of Douglas, ss:

............Trawn Griffin..........................., being duly sworn, deposes and says that he is an employee of The Omaha World-Herald, a legal daily newspaper printed and published in the county of Douglas and State of Nebraska, and of general circulation in the Counties of Douglas and Sarpy and State of Nebraska, and that the attached printed notice was published in the said newspaper on the ..6th... day of ......March.......................... A. D., 20 .06.,
and that said newspaper is a legal newspaper under the statues of the State of Nebraska. The above facts are within my personal knowledge. The Omaha World-Herald has an average circulation of .195,196..... daily 242,227....... Sunday, in 20 .06 .

(Signed) ...Trawn Griffin... Title: Advertising..................

Subscribed in my presence and sworn to before me this ...6th............ day of ....March........ 20 . . .06

Debra L. Marco

Notary Public

GENERAL NOTARY - State of Nebraska
DEBRA L. MARCO
MY COMMISSION EXPIRES
September 13, 2007

Printer's Fee $...249.48...
Affidavit ....
Paid by ....

313-G8-007

Appendix B

NEBRASKA ADMINISTRATIVE CODE

TITLE 457 – DEPARTMENT OF NATURAL RESOURCES
RULES FOR SURFACE WATER

ALPHABETICAL TABLE OF CONTENTS

SUBJECT OF TITLE	STATUTORY AUTHORITY	CODE SECTION
Applications for New Water Appropriations	§ 46-241 § 46-242 § 61-206	002
Authority to Levy Fees	§ 46-206 § 46-207 § 46-2,101 § 46-2,102	017
Change of Address	§ 46-230 § 61-206	005
Change of Ownership of Appropriation	§ 46-230 § 61-206 § 76-2,124	004
Changing Point of Diversion	§ 46-250 § 61-206	006
Claims	§ 46-202 § 61-206 § 84-909(1)	014
Dam Hazard Classification	§ 46-257 § 61-206	019
Definitions	§ 46-250 § 61-206	001

SUBJECT OF TITLE	STATUTORY AUTHORITY	CODE SECTION
Determination of Fully Appropriated Basins, Sub-Basins or Reaches	§ 46-713	024
Engineering Drawings and Specifications for Dams	§ 46-257 § 61-206	012
Height of Dam	§ 33-105 § 61-206	008
Incidental and Intentional Underground Water Storage	§ 46-226.01 § 46-297 § 61-206	016
Induced Ground Water Recharge	§ 46-233 § 46-235 § 61-206 § 61-207	022
Instream Flows	§ 46-2,110 § 46-2,114 § 61-206 § 61-207	018
Moratorium Area Variances	§ 46-714 § 61-206	023
Outlet Works	§ 46-241 § 61-206	013
Permit to Conduct Water in Stream Channels	§ 46-252 § 61-206 § 61-207	021
Project Maps for the Impoundment of Water	§ 46-237 § 46-241 § 61-206	011
Project Maps for the Use of Water	§ 46-237 § 46-294 § 61-206	010
Relinquishments	§ 61-206	003

SUBJECT OF TITLE	STATUTORY AUTHORITY	CODE SECTION
Temporary Use Permits	§ 46-233 § 61-206	020
Theoretical Horsepower	§ 33-105 § 61-206	007
Transfer the Location of Use	§§ 46-290 – 294 § 61-206	009

NEBRASKA ADMINISTRATIVE CODE

TITLE 456 – DEPARTMENT OF NATURAL RESOURCES
RULES FOR SURFACE WATER

NUMERICAL TABLE OF CONTENTS

SUBJECT OF TITLE	STATUTORY AUTHORITY	CODE SECTION
Definitions	§ 46-250 § 61-206	001
Applications for New Water Appropriations	§ 46-241 § 46-242 § 61-206	002
Relinquishments	§ 61-206	003
Change of Ownership of Appropriation	§ 46-230 § 61-206 § 76-2,124	004
Change of Address	§ 46-230 § 61-206	005
Changing Point of Diversion	§ 46-250 § 61-206	006
Theoretical Horsepower	§ 33-105 § 61-206	007
Height of Dam	§ 33-105 § 61-206	008
Transfer the Location of Use	§§ 46-290 – 294 § 61-206	009

SUBJECT OF TITLE	STATUTORY AUTHORITY	CODE SECTION
Project Maps for the Use of Water	§ 46-237 § 46-294 § 61-206	010
Project Maps for the Impoundment of Water	§ 46-237 § 46-241 § 61-206	011
Engineering Drawings and Specifications for Dams	§ 46-257 § 61-206	012
Outlet Works	§ 46-241 § 61-206	013
Claims	§ 46-202 § 61-206 § 84-909(1)	014
Incidental and Intentional Underground Water Storage	§ 46-226.01 § 46-297 § 61-206	016
Authority to Levy Fees	§ 46-206 § 46-207 § 46-2,101 § 46-2,102	017
Instream Flows	§ 46-2,110 § 46-2,114 § 61-206 § 61-207	018
Dam Hazard Classification	§ 46-257 § 61-206	019
Temporary Use Permits	§ 46-233 § 61-206	020
Permit to Conduct Water in Stream Channels	§ 46-252 § 61-206 § 61-207	021

SUBJECT OF TITLE	STATUTORY AUTHORITY	CODE SECTION
Induced Ground Water Recharge	§ 46-233 § 46-235 § 61-206 § 61-207	022
Moratorium Area Variances	§ 46-714 § 61-206	023
Determination of Fully Appropriated Basins, Sub-Basins or Reaches	§ 46-713	024

APPROVED

DEC 04 2006

BD

Dave Heineman
DAVE HEINEMAN
GOVERNOR

NEBRASKA ADMINISTRATIVE CODE

APPROVED
JON BRUNING
ATTORNEY GENERAL
BY
Assistant Attorney General
DATE 10-30-06

Title 457 - DEPARTMENT OF NATURAL RESOURCES
RULES FOR SURFACE WATER

Chapter 24 - DETERMINATION OF FULLY APPROPRIATED BASINS, SUB-BASINS OR REACHES

001 FULLY APPROPRIATED. Pursuant to Neb. Rev. Stat. § 46-713(3) (Reissue 2004, as amended), a river basin, subbasin, or reach shall be deemed fully appropriated if the Department of Natural Resources determines that then-current uses of hydrologically connected surface water and ground water in the river basin, subbasin, or reach cause or will in the reasonably foreseeable future cause (a) the surface water supply to be insufficient to sustain over the long term the beneficial or useful purposes for which existing natural flow or storage appropriations were granted and the beneficial or useful purposes for which, at the time of approval, any existing instream appropriation was granted, (b) the streamflow to be insufficient to sustain over the long term the beneficial uses from wells constructed in aquifers dependent on recharge from the river or stream involved, or (c) reduction in the flow of a river or stream sufficient to cause noncompliance by Nebraska with an interstate compact or decree, other formal state contract or agreement, or applicable state or federal laws.

001.01A Except as provided in 001.01C below, for purposes of Section 46-713(3)(a), the surface water supply for a river basin, subbasin, or reach shall be deemed insufficient, if, after considering the impact of the lag effect from existing groundwater pumping in the hydrologically connected area that will deplete the water supply within the next 25 years, it is projected that during the period of May 1 through September 30, inclusive, the most junior irrigation right will be unable to divert sufficient surface water to meet on average eighty-five percent of the annual crop irrigation requirement, or, during the period of July 1 through August 31, inclusive, will be unable to divert sufficient surface water to meet at least sixty-five percent of the annual crop irrigation requirement.

For purposes of this rule, the "annual crop irrigation requirement" will be determined by the annual irrigation requirement for corn. This requirement is based on the average evapotranspiration of corn that is fully watered to achieve the maximum yield and the average amount of precipitation that is effective in meeting the crop water requirements for the area.

The inability to divert will be based on stream flow data and diversion records, if such records are available for the most junior surface water appropriator. If these records are not available, the inability to divert will be based on the average number of days within each time period (May 1 to September 30 and July 1 to August 31) that the most junior surface water appropriation for irrigation would have been closed by the Department and therefore could not have diverted during the previous 20 year period. In making this

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calculation, if sufficient stream flow data and diversion data are not available, it will be assumed that if the appropriator was not closed, the appropriator could have diverted at the full permitted diversion rate. In addition the historical record will be adjusted to include the impacts of all currently existing surface water appropriations and the projected future impacts from currently existing ground water wells. The projected future impacts from ground water wells to be included shall be the impacts from ground water wells located in the hydrologically connected area that will impact the water supply over the next 25 year period.

001.01B In the event that the junior water rights are not irrigation rights, the Department will utilize a standard of interference appropriate for the use, taking into account the purpose for which the appropriation was granted.

001.01C If, at the time of the priority date of the most junior appropriation, the surface water appropriation could not have diverted surface water a sufficient number of days on average for the previous 20 years to satisfy the requirements of 001.01A, the surface water supply for a river basin, subbasin, or reach in which that surface water appropriation is located shall be deemed insufficient only if the average number of days surface water could have been diverted over the previous 20 years is less than the average number of days surface water could have been diverted for the 20 years previous to the time of the priority date of the appropriation.

When making this comparison, the calculations will follow the same procedures as described in 001.01A. When calculating the number of days an appropriator could have diverted at the time of the priority date of the appropriation, the impacts of all appropriations existing on the priority date of the appropriation and the impacts of wells existing on the priority date of the appropriation shall be applied in the same manner as in 001.01A. As in 001.01A above, in making this calculation, if sufficient stream flow data and diversion data are not available, it will be assumed that if the appropriator was not closed, the appropriator could have diverted at the full permitted diversion rate.

Use of the method described in this rule is not intended to express or imply any mandate or requirement that the method used herein must be included in the goals and objectives of any integrated management plan adopted for a river basin, subbasin or reach determined to be fully appropriated under this rule. Further, nothing in this section is intended to express or imply a priority of use between surface water uses and ground water uses.

001.02 The geographic area within which the Department preliminarily considers surface water and ground water to be hydrologically connected for the purpose prescribed in Section 46-713(3) is the area within which pumping of a well for 50 years will deplete the river or a base flow tributary thereof by at least 10% of the amount pumped in that time.

002 INFORMATION CONSIDERED. For making preliminary determinations required by Neb. Rev. Stat. Section 46-713 (Reissue 2004, as amended) the Department will use the best

DEC 4 2006

scientific data and information readily available to the Department at the time of the determination. Information to be considered will include:

Surface water administrative records
Department Hydrographic Reports
Department and United States Geological Survey stream gage records
Department's registered well data base
Water level records and maps from Natural Resources Districts, the Department, the University of Nebraska, the United States Geological Survey or other publications subject to peer review
Technical hydrogeological reports from the University of Nebraska, the United States Geological Survey or other publications subject to peer review
Ground water models
Current rules and regulations of the Natural Resources Districts

The Department shall review this list periodically, and will propose amendments to this rule as necessary to incorporate scientific data and information that qualifies for inclusion in this rule, but was not available at the time this rule was adopted.

APPROVED
DEC 04 2006
Dave Heineman
DAVE HEINEMAN

APPROVED
JON BRUNING
ATTORNEY GENERAL
BY...........................
Assistant Attorney General
DATE 10-30-06

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By .... SECRETARY OF STATE

Appendix C

Basic Assumptions Used in the Development of the Department of Natural Resources Proposed Method to Determine Whether a Stream and the Hydrologically Connected Ground Water Aquifers Are Fully Appropriated

Nebraska Revised Statutes § 46-713(3) states that a river basin subbasin or reach shall be deemed fully appropriated if the department determines that then-current uses of hydrologically connected surface water and ground water in the river basin, subbasin, or reach cause or will in the reasonably foreseeable future cause: (a) the surface water supply to be insufficient to sustain over the long term the beneficial or useful purposes for which existing natural flow or storage appropriations and the beneficial or useful purposes for which, at the time of approval, any existing instream appropriation was granted, (b) the streamflow to be insufficient to sustain over the long term the beneficial uses from wells constructed in aquifers dependent on recharge from the river or stream involved and (c) reduction in the flow of a river or stream sufficient to cause noncompliance by Nebraska with an interstate compact or decree, or other formal state contract or agreement, or applicable state off federal laws. This memo will address the assumptions relied upon to develop the method the Department proposes to use to address sections a and b of the statute.

In essence, if streamflow is sufficient enough to supply surface water appropriators, it is also sufficient to supply recharge for ground water wells dependent on the streamflow. This is true because any ground water aquifer that is hydrologically connected to a fully appropriated stream is also fully appropriated because the surface water and hydrologically connected ground water are both part of one interconnected system. A depletion in one component of this system depletes the other component. If there is an additional well and consumptive use of water in the ground water aquifers connected to the stream, the new well will either intercept and consume water that otherwise would have flowed to the stream or cause more water to flow from the stream to the aquifer. Eventually this additional consumption will cause not only additional depletions to the aquifer, but also additional depletions to the stream. In essence, the test of looking at the sufficiency of streamflow to satisfy a junior surface water right is like a canary in the coal mine; the junior water rights act as an alarm system signaling that the stream and the hydrologically connected ground water aquifers are both fully appropriated.

The nature of the connection between the stream and the aquifer determines how much and how fast water will flow between the stream and the aquifer. Water flows from a hydrologically connected aquifer to a stream, or vice versa, in response to the difference in the hydraulic head between the stream and the aquifer. Water flows down the hydraulic head gradient from areas of higher hydraulic head to areas of lower hydrologic head. Hydraulic head in ground water is a function of the combination of both the elevation and the pressure of the water. Water flows downhill in response to gravity and uphill in response to pressure from the weight of overlying aquifer materials and water.

In the case of a gaining stream, the water in the aquifer has a higher hydraulic head than the stream and water flows down gradient from the aquifer to the stream. In this situation, the addition of a pumping ground water well that removes water from the aquifer will lower the hydraulic head of the ground water in the aquifer and decrease the gradient between the higher hydraulic head in the aquifer and the lower hydraulic head in the stream. The decrease in the hydraulic gradient results in less water flowing from the aquifer to the stream.

In the case of a losing stream the water in the stream is at a higher hydraulic head than the ground water and water flows down gradient from the stream to the aquifer. As before, the addition of a pumping ground water well that removes water from the aquifer will lower the hydraulic head of the ground water in the aquifer. In this case the well will increase the hydraulic gradient between the higher head of the stream and the lower head in the aquifer and more water will flow from the stream to the aquifer, further depleting the stream. In either case, if the stream itself is already determined to be fully appropriated, than the whole integrated system must be fully appropriated.

One must also ask, is it possible for a stream itself to have sufficient water for all surface water rights but not have sufficient ground water to recharge wells dependent on streamflow? In this case, all the demands of the surface water rights would have to be satisfied, but the water in the ground water aquifer would be insufficient for the existing wells. Such a system could not happen on a gaining stream because if the ground water were insufficient to sustain the wells, there would be little or no water in the stream for the surface water users. According to Bentall and Shafer (1979) most streams in the State of Nebraska are gaining streams[1].

The remaining case would be a losing stream on which the major water supply to the stream and the hydrologically connected aquifers was from surface water runoff to the stream. Furthermore, this runoff would have to be sufficient to satisfy the junior surface water rights, or it would be determined to be fully appropriated under criteria (a) of the statute, but not sufficient enough to satisfy ground water wells for which the stream flow was a critical component of the supply. In areas on the White and Hat Creeks in western Nebraska, where isolated fractures in the Brule Formation are in close hydrologic connection to the stream but not to a surrounding ground water aquifer, there could be small stock and domestic wells that depend primarily on streamflow as their sole source of water. However, these streams have already been declared fully appropriated because the demands of the existing surface water rights are not met. There may also be such

[1] Availability and Use of Water in Nebraska 1975. 1979. Nebraska Water Survey Paper Number 48. Conservation and Survey Division Institute of Agriculture and Natural Resources, University of Nebraska Lincoln.

isolated physical systems in other parts of the state such as in the glacial till area of the eastern part of the state and along the Missouri River, but like the White River and Hat Creek, if the demands of the hydrologically wells are not being met, it is unlikely that the demands of any existing surface water rights would be met.

Appendix D

Net Irrigation Requirement[1]

Background

The net irrigation water requirement (INET) is the net amount of water that must be applied by irrigation to supplement stored soil water and precipitation and supply the water required for the full yield of an irrigated crop. INET does not include irrigation water that is not available for crop water use such as irrigation water that percolates through the crop root zone or that runs off of the irrigated field. INET as used in this application is the annual amount of water and is expressed in units of acre-inches of water per acre of irrigated land for a year. Since corn is the most widely irrigated crop in Nebraska, the net irrigation requirement was simulated for corn grown on fine sandy loam soil. The soil used in the simulations holds about 1.75 inches of available water per foot of soil depth. The soil used for the simulations represents an average condition of soils across Nebraska.

Procedure

The net irrigation requirement can be computed using several methods. Early methods relied on the difference between the evapotranspiration (ET) required for full crop yields minus the amount of precipitation during the irrigation season that is estimated to be effective in meeting crop water requirements. This method was generally applied on a monthly basis and did not consider precipitation or soil water rewetting during the portion of the year when crops were not growing, or the effects of individual precipitation events. This method has given way to daily calculations of the soil water balance of irrigated crops.

A computer simulation model (CROPSIM) developed at the University of Nebraska-Lincoln by Dr. Derrel Martin was used to compute the daily water balance for irrigated corn and INET for an array of weather stations across the state. Computations with the CROPSIM program for data from selected weather stations were used to generate the map of net irrigation water requirements for corn grown on a fine sandy loam soil.

The CROPSIM model maintains a daily soil water balance including the following terms:

$$D_i = D_{i-1} + ET_c + DP + RO - P - I_{net}$$

where D_i is the available soil water depletion on day i, inches
D_{i-1} is the depletion on the previous day, inches
ET_c is the daily evapotranspiration rate, inches/day
DP is the daily deep percolation from the root zone, inches/day
RO is the daily run off from the irrigated land due to rainfall, inches/day
P is the daily precipitation, inches/day
I_{net} is the net irrigation that is applied on day i, inches/day.

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[1] Prepared by Derrel Martin, Professor of Irrigation and Water Resources Engineering, Department of Biological Systems Engineering, University of Nebraska-Lincoln, Lincoln, NE. 68583-0726.

The daily soil water depletion is maintained in the model. Irrigations are applied on days when the depletion reaches a specified amount for the crop root zone. Irrigations were applied when more than half of the available water in the top four feet of the root zone was depleted. This is a common management practice used to schedule irrigation. The net irrigation applied each irrigation resembles practices typical of center pivot irrigation. This involved applying a gross irrigation of one inch each application which equaled a net irrigation of 0.85 inches per irrigation. Irrigations did not begin until the corn crop had begun vegetative growth. Irrigations were continued for the year until the corn crop had reached a growth stage where water stress has minimal affects on yield. This stage generally matches a hard-dent growth stage for corn.

The CROPSIM program depends on evapotranspiration (ET) to compute the soil water depletion and determine dates for irrigation. The ET for corn was computed in the model using a reference crop evapotranspiration (ETr) that represents the amount of energy available from the environment to evaporate water. The reference crop evapotranspiration is multiplied by a crop coefficient (Kc) to compute the water use of corn:

$$ETc = Kc\ ETr$$

A tall reference crop often considered to be alfalfa about 20 inches in height was used for the reference crop evapotranspiration. The Standardized Penman-Monteith method developed by the ASCE-EWRI[2] task force was used as the basis for computing ETr. Since climatic data needed for the Penman-Monteith method are not available dating back to 1950, the Hargreaves[3] method was calibrated to the Penman-Monteith method for a period of about 20 years for selected weather stations that are part of the Automated Weather Data Network operated by the High Plains Climate Center at the University of Nebraska-Lincoln. The calibrated Hargreaves method provides daily estimates of reference crop ET for the CROPSIM model to simulate corn ET and net irrigation requirements for the period from 1950 through 2004. The fifty-five year period was used to include climatic variations that are expected in the Great Plains. The Hargreaves method was calibrated for each month using the ASCE Hourly method for an alfalfa (tall) reference crop. Data were used from the 23 automated weather data network stations listed in Table 1. The automated weather stations were selected to provide statewide coverage and a period long enough to represent climatic variations across the state. The location of the automated weather data network (AWDN) stations are shown in Figure 1. The map shows that the AWDN stations are well distributed across the state.

[2] ASCE-EWRI. 2005. The ASCE Standardized Reference Evapotranspiration Equation. Environmental and Water Resources Institute of the American Society of Civil Engineers, Standardization of Reference Evapotranspiration Task Committee. ASCE. Reston, NY.

[3] Hargreaves, G.H. and R,G. Allen. 2003. History and evaluation of Hargreaves evapotranspiration equation. Journal of Irrigation and Drainage Engineering. ASCE. 129(1): 53-63.

Table 1. Automated weather data network stations used to calibrate the Hargreaves method to the sum-of-hourly for daily reference ET for a tall reference crop (i.e., alfalfa). The date the system first became operational and the latitude, longitude and elevation of the stations are also listed.

Station	**Latitude degrees North**	**Longitude, degrees west**	**Elevation, meters**	**Month**	**Day**	**Year**
AINSWORTH	42.550	-99.817	765	6	4	1984
ALLIANCEWEST	42.017	-103.133	1213	5	29	1988
BEATRICE	40.300	-96.933	376	1	1	1990
CENTRALCITY	41.150	-97.967	517	9	4	1986
CHAMPION	40.400	-101.717	1029	5	20	1981
CLAY CENTER(SC)	40.567	-98.133	552	7	14	1982
CONCORD(NE)	42.383	-96.950	445	7	16	1982
DICKENS	40.950	-100.967	945	5	21	1981
ELGIN	41.933	-98.183	619	1	1	1988
GORDON	42.733	-102.167	1109	10	18	1984
GUDMUNDSENS	42.067	-101.433	1049	10	5	1982
HOLDREGE	40.333	-99.367	707	5	29	1988
LEXINGTON	40.767	-99.733	728	8	5	1986
MCCOOK	40.233	-100.583	792	5	21	1981
MEADTURFFARM	41.167	-96.467	366	7	29	1986
MITCHELL FARMS	41.933	-103.700	1098	7	11	1996
NEBRASKA CITY	40.533	-95.800	328	6	29	1998
ONEILL	42.467	-98.750	625	7	17	1985
ORD	41.617	-98.933	625	7	10	1983
SCOTTSBLUFF	41.883	-103.667	1208	1	1	1991
SIDNEY	41.217	-103.017	1317	12	1	1982
WESTPOINT	41.850	-96.733	442	5	15	1982
YORK	40.867	-97.617	490	4	22	1996

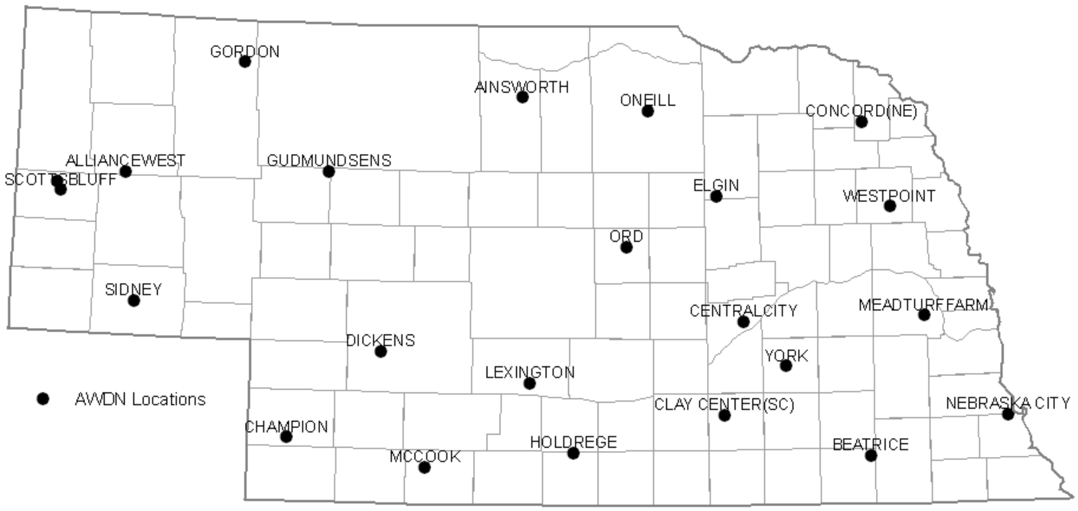


Figure 1. Location of automated weather stations used to calibrate the Hargreaves method.

The daily reference crop ET for alfalfa was calibrated using the following equation:

$$ETr = \left[a + b\ Long^2 \right] Hg^c$$

where ETr is daily reference crop ET for alfalfa as computed with the ASCE method, and
Long is the longitude, degrees
Hg is the Hargreaves factor,
and a, b and c are empirical coefficients.

The Hargreaves factor is computed as:

$$Hg = \frac{(Ta + 17.8)\sqrt{T\max - T\min}\ \ Ra}{\lambda}$$

where Ta is the average daily temperature, °C,
Tmax is the maximum daily temperature, °C,
Tmin is the minimum daily temperature, °C,
Ra is the extraterrestrial radiation, $MJ/m^2/day$,
8 is the heat of vaporization = 2.45 MJ/Kg of water.

Daily data from the AWDN stations were used to compute daily ETr values with the Penman-Monteith method. The Hargreaves factor was compute for each day as well. The results of the computations were separated by month and the coefficients for the calibrated Hargreaves method (*i.e.*, a, b and c) were computed from the regression analysis for all 23 AWDN stations. The results of the calibration are listed in Table 2. The coefficients of determination (r^2) for the monthly values are reasonably good for all months.

Table 2. Parameters and coefficient of determination for calibration of Hargreaves method to Sum-of-Hourly calculations for ASCE Penman-Monteith.

Month	a	b	c	r^2
January	-2.97117E-03	6.68252E-07	1.0400	0.68
February	-2.10020E-03	4.71103E-07	1.0746	0.74
March	-1.99470E-04	1.60011E-07	1.1419	0.76
April	3.42244E-04	2.06925E-08	1.2499	0.76
May	1.48641E-04	1.16248E-08	1.3282	0.65
June	1.13210E-04	8.14170E-10	1.4143	0.66
July	6.58766E-05	5.44612E-09	1.4072	0.66
August	4.65366E-05	2.19358E-08	1.3122	0.62
September	3.90011E-04	7.01456E-08	1.1518	0.62
October	9.59964E-04	1.20508E-07	1.0839	0.65
November	-1.08578E-03	3.78426E-07	1.0814	0.68
December	-4.57939E-03	8.95039E-07	1.0180	0.66

Simulation of crop water use for the period from 1950 through 2004 required a different set of weather stations since AWDN data are not available before 1980. Sixty-two cooperator or National Weather Service stations were selected for the simulation. Stations that were selected included measurements for at least the maximum daily air temperature, the minimum daily air temperature and daily precipitation (rain and snow). Some stations also included evaporation measurements from evaporation pans. These data were not used in the simulation. Weather stations were selected to represent the state as indicated by the climate zones shown in Figure 2. Only stations that included daily weather data starting before 1949 were selected for analysis. The High Plains Climate Center has developed data management routines to estimate values for days when data are missing or appear to be incorrect. Therefore, none of the stations have missing data and no procedures were developed to correct these data which are referred to as National Weather Station (NWS) stations in this report.

The CROPSIM model uses a set of parameters to describe how corn develops during the year and to represent typical management practices for a region. To simulate corn growth the state wad divided into four management zones as shown in Figure 3. The management zones in Figure 3 generally align with the Climate Zones in Figure 2 except for the North Central Climate Zone. This zone was divided approximately in half to represent management practices for that region. Some important parameters for the management zones are included in Table 3. The data show that the amount of growing degree days required for crop development increases as one progresses from management zone 1 east to management zone 4. Planting is also generally delayed as one progresses west from zone 3. A slightly later planting date was used for management zone 4 since this region receives more rain in the spring that can delay planting compared to zone 3. Other parameters used to simulate crop growth and management are listed in Table 2. These values were held constant across all four management zones.

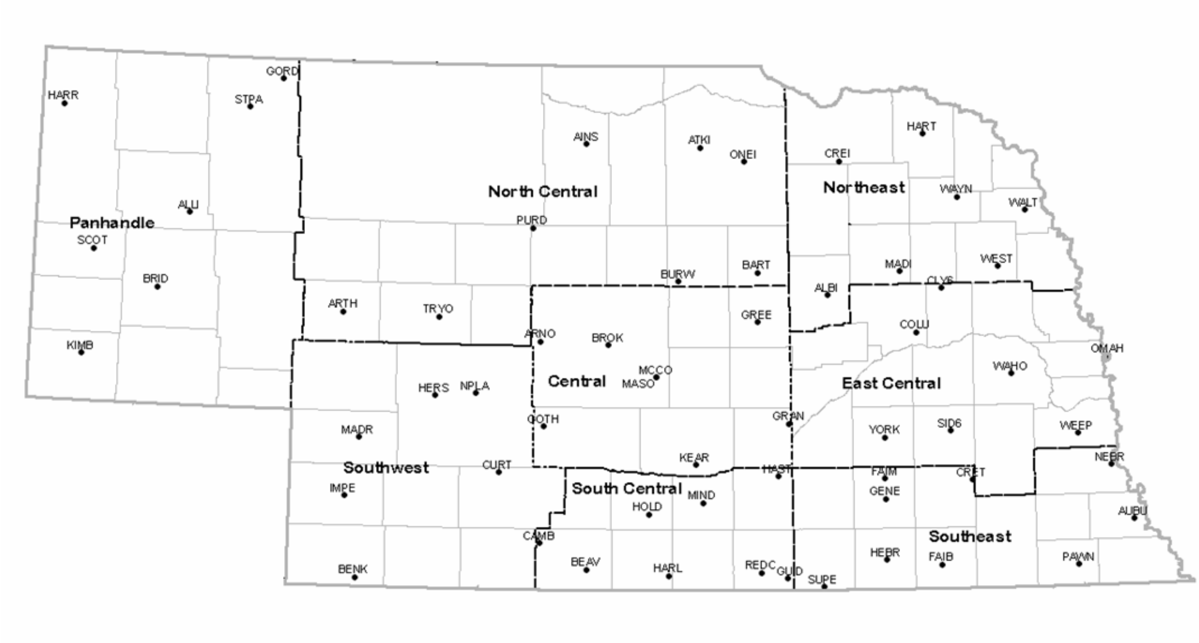


Figure 2. Location of National Weather Service stations used in simulations and Climatic Zones for Nebraska. Specific information for the NWS stations is included in Table 4.

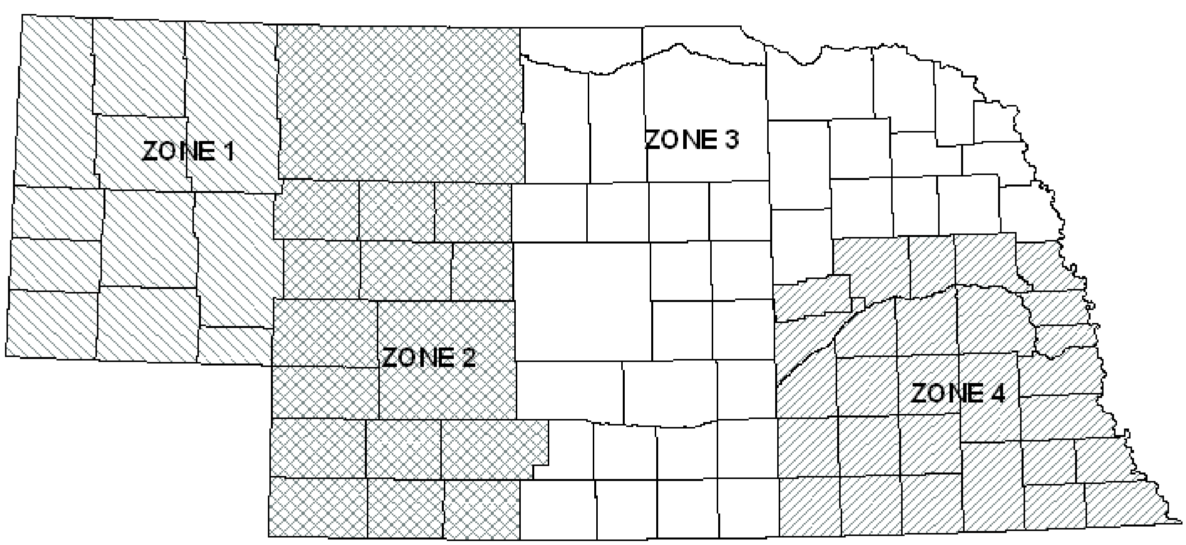


Figure 3. Location of management zones for the CROPSIM model.

Table 3. Parameters used in simulation of crop growth with the CROPSIM model.

Management Zone	Growing Degree Days for Specific Growth Stages					
	Planting Date	Begin of Flowering	Begin of Ripening	Yield Formation	Effective Cover	Physiological Maturity
Zone 1	5/5	1200	1700	2160	1050	2400
Zone 2	5/1	1300	1800	2500	1200	2750
Zone 3	4/25	1350	1850	2600	1250	2850
Zone 4	5/1	1400	1850	2700	1300	2950
Minimum Depth of Crop Root Zone, inches						6
Maximum Depth of Crop Root Zone, inches						72
Growing Degree Days for Start of Root Growth						200
Growing Degree Days for Start of Vegetative Growth						450
Depth of Soil Profile Used for Irrigation Management, inches						48

Runoff was simulated using the curve number method originally developed by the USDA Natural Resources Conservation Service. The method was modified to adjust curve numbers based on the soil water content at the time of precipitation. The soil water content adjustment of curve numbers, and melting and infiltration of snow was based on routines in the SWAT[4] model. The fine sandy loam soil has been characterized as being in hydrologic group B in the curve number method.

Results

The net irrigation requirement and the amount of evapotranspiration for fully irrigated corn and non-irrigated corn grown on fine sandy loam was simulated at sixty-two NWS stations across Nebraska for the period from 1949 through 2004. Data for 1949 were not included in the analysis as there is usually a stabilization period following the initial conditions used for the soil water content for the first year of simulation for a site. The difference in the evapotranspiration for fully irrigated corn and non-irrigated corn is the consumptive irrigation requirement (CIR). The CIR is the amount of consumptive use of water due to irrigating for full crop yield. Results of the simulations for the NWS stations are summarized in Table 4. The net irrigation requirement was used to develop contour lines for the net irrigation map across the state (Figure 4). The results generally show that irrigation requirements increase in a southeast-northwest pattern.

[4] Arnold, J.G. and N. Fohrer. 2005. SWAT2000: current capabilities and research opportunities in applied watershed modeling. Hydrol. Process. 19(3):563-572.

Table. 4. Results of simulations for ET, CIR and net irrigation for NWS weather stations used in the analysis.

Site	ET Full Yield, Inches/Year	ET Non Irrigated, Inches/Year	CIR, Inches /Year	Net Irrigation, Inches/Year	Latitude, Degrees	Longitude, Degrees	Elevation, Meter	Climate Division	Station Code	Station Name
AINS	29.86	20.48	9.38	10.45	42.55	-99.85	765	2	c250050	AINSWORTH
ALBI	29.65	23.03	6.63	8.41	41.68	-98.00	546	3	c250070	ALBION
ALLI	28.81	15.65	13.15	13.97	42.10	-102.88	1217	1	c250130	ALLIANCE 1 WNW
ARNO	32.07	19.75	12.32	13.09	41.42	-100.18	838	4	c250355	ARNOLD
ARTH	30.12	17.93	12.19	13.21	41.57	-101.68	1067	2	c250365	ARTHUR
ATKI	29.28	20.88	8.40	9.67	42.53	-98.97	643	2	c250420	ATKINSON
AUBU	28.70	24.84	3.86	6.00	40.37	-95.73	283	8	c250435	AUBURN 5 ESE
BART	30.14	22.11	8.03	9.58	41.82	-98.53	652	2	c250525	BARTLETT 4 S
BEAV	33.37	21.01	12.36	13.21	40.12	-99.82	658	7	c250640	BEAVER CITY
BENK	31.25	17.78	13.47	14.37	40.05	-101.53	922	6	c250760	BENKELMAN
BRID	30.01	15.67	14.34	14.85	41.67	-103.10	1117	1	c251145	BRIDGEPORT
BROK	30.75	20.51	10.23	11.30	41.40	-99.67	762	4	c251200	BROKEN BOW 2 W
BURW	30.67	20.59	10.08	11.16	41.77	-99.13	663	2	c251345	BURWELL 4 SE
CAMB	31.23	19.77	11.46	12.16	40.27	-100.17	689	7	c251415	CAMBRIDGE
CLY6	29.59	22.88	6.71	8.07	40.50	-97.93	530	8	c251680	CLAY CENTER 6 ESE
COLU	28.05	22.67	5.38	7.11	41.47	-97.33	442	5	c251825	COLUMBUS 3 NE
CREI	29.63	22.06	7.58	9.16	42.45	-97.90	497	3	c251990	CREIGHTON
CRET	28.67	23.78	4.89	6.80	40.62	-96.93	437	8	c252020	CRETE
CURT	31.22	19.38	11.84	13.15	40.67	-100.48	829	6	c252100	CURTIS 3 NNE
FAIB	29.92	24.67	5.25	7.09	40.13	-97.17	415	8	c252820	FAIRBURY
FAIM	29.64	22.83	6.81	8.30	40.63	-97.58	500	8	c252840	FAIRMONT
GENE	28.27	23.16	5.11	6.91	40.52	-97.58	497	8	c253175	GENEVA
GORD	28.79	16.89	11.90	13.20	42.88	-102.20	1128	1	c253355	GORDON 6 N

GOTH	30.89	20.18	10.70	11.39	40.93	-100.15	788	4	c253365	GOTHENBURG
GRAN	28.70	21.27	7.43	8.89	40.95	-98.30	561	4	c253395	GRAND ISLAND WSO AP
GREE	30.87	22.15	8.73	10.20	41.53	-98.53	616	4	c253425	GREELEY
GUID	29.48	22.43	7.05	8.72	40.07	-98.32	498	7	c253485	GUIDE ROCK
HARL	30.17	20.70	9.47	10.35	40.08	-99.20	610	7	c253595	HARLAN COUNTY LAKE
HARR	28.11	16.25	11.87	13.85	42.68	-103.88	1478	1	c253615	HARRISON
HART	28.72	22.05	6.67	8.35	42.60	-97.25	418	3	c253630	HARTINGTON
HAST	29.93	23.08	6.85	8.55	40.65	-98.38	591	7	c253660	HASTINGS 4 N
HEBR	29.51	23.75	5.77	7.46	40.17	-97.58	451	8	c253735	HEBRON
HERS	30.51	18.47	12.04	13.21	41.10	-100.97	900	6	c253810	HERSHEY 5 SSE
HOLD	30.09	22.02	8.07	9.41	40.43	-99.35	707	7	c253910	HOLDREGE
IMPE	29.85	18.30	11.56	12.67	40.52	-101.63	999	6	c254110	IMPERIAL
KEAR	29.72	21.70	8.03	9.37	40.72	-99.00	649	4	c254335	KEARNEY 4 NE
KIMB	30.38	16.60	13.78	14.51	41.27	-103.65	1451	1	c254440	KIMBALL
MADI	29.19	22.81	6.39	8.27	41.82	-97.45	511	3	c255080	MADISON 2 W
MADR	31.45	18.73	12.72	13.77	40.85	-101.53	975	6	c255090	MADRID
MASO	30.30	21.65	8.65	9.83	41.22	-99.30	689	4	c255250	MASON CITY
MCCO	29.05	19.31	9.74	11.14	40.20	-100.62	771	6	c255310	MCCOOK
MIND	29.60	21.79	7.80	9.20	40.50	-98.95	658	7	c255565	MINDEN
NEBR	28.48	24.88	3.60	5.61	40.68	-95.88	329	8	c255810	NEBRASKA CITY
NPLA	29.45	18.64	10.81	12.13	41.12	-100.67	847	6	c256065	NORTH PLATTE WSO ARP
OMAH	27.31	23.98	3.33	5.39	41.30	-95.88	304	5	c256255	OMAHA EPPLEY AIRFIEL
ONEI	30.20	21.30	8.90	10.15	42.45	-98.63	607	2	c256290	ONEILL
PAWN	29.13	24.66	4.48	6.63	40.12	-96.15	369	8	c256570	PAWNEE CITY
PURD	31.79	19.67	12.12	12.98	42.07	-100.25	820	2	c256970	PURDUM
REDC	31.29	22.46	8.83	10.35	40.10	-98.52	524	7	c257070	RED CLOUD
SCOT	29.43	14.72	14.72	15.36	41.87	-103.60	1202	1	c257665	SCOTTSBLUFF AP

SID6	29.43	15.99	13.44	14.14	41.20	-103.02	1317	1	c257830	SIDNEY 6 NNW
STPA	28.30	21.10	7.20	8.64	41.27	-98.47	541	4	c257515	ST PAUL 4 N
SUPE	29.68	23.05	6.63	8.27	40.02	-98.05	482	8	c258320	SUPERIOR
TRYO	30.53	18.30	12.23	13.34	41.55	-100.95	990	2	c258650	TRYON
WAHO	29.47	25.01	4.47	6.68	41.22	-96.62	387	5	c258905	WAHOO
WALT	29.22	23.18	6.05	7.93	42.15	-96.48	372	3	c258935	WALTHILL
WAYN	28.91	22.50	6.41	8.05	42.23	-97.00	445	3	c259045	WAYNE
WEEP	28.49	24.41	4.08	6.17	40.87	-96.13	335	5	c259090	WEEPING WATER
WEST	28.30	23.30	5.00	7.09	41.83	-96.70	399	3	c259200	WEST POINT
YORK	28.78	23.19	5.59	7.31	40.87	-97.58	491	5	c259510	YORK

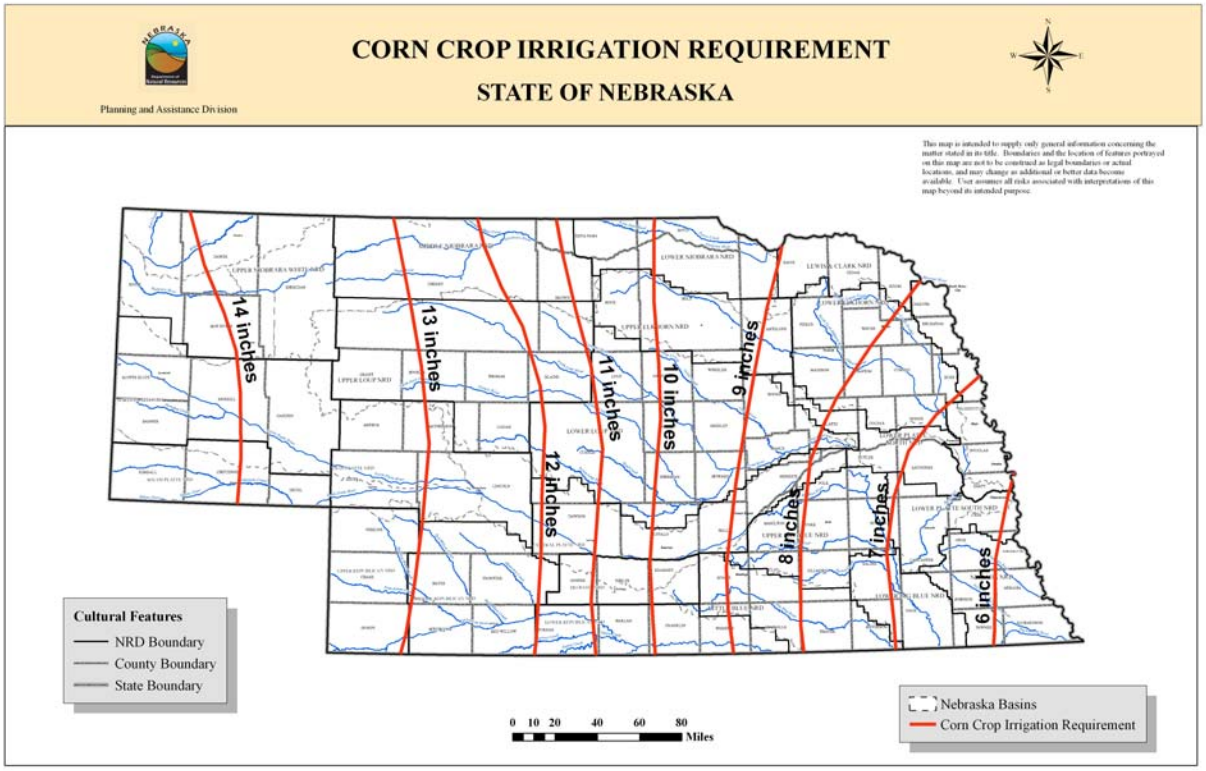
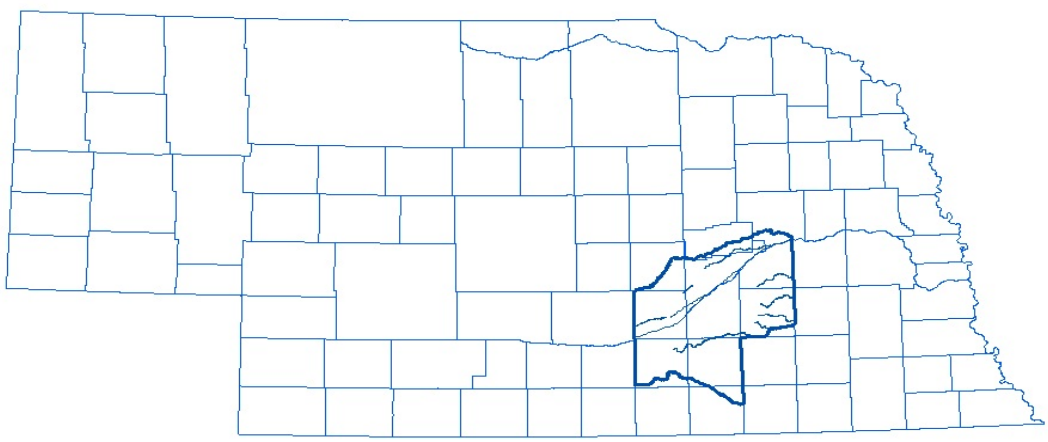


Figure 4. Map of net irrigation requirements (inches/year) for corn grown on fine sandy loam.

Appendix E

A GROUNDWATER MODEL TO DETERMINE THE AREA WITHIN THE UPPER BIG BLUE NATURAL RESOURCES DISTRICT WHERE GROUNDWATER PUMPING HAS THE POTENTIAL TO INCREASE FLOW FROM THE PLATTE RIVER TO THE UNDERLYING AQUIFER BY AT LEAST 10 PERCENT OF THE VOLUME PUMPED OVER A 50-YEAR PERIOD



Prepared By
R.J. Bitner, P.E.
Upper Big Blue Natural Resources District
September 2005

ACKNOWLEDGMENTS

The following persons provided assistance with inputs and reviews that were incorporated into the model and final report:

Courtney Hemenway, P.E., Hemenway Groundwater Engineering, Inc., provided a peer review of the model development, model inputs, model application, and report to ensure that these components are developed in accordance with acceptable standards.

Duane Woodward, Hydrologist, Central Platte Natural Resources District, reviewed the model and inputs for consistency with COHYST standards. Duane also assisted with evaluating recent river bed conductance data that was incorporated into the model.

Steve Peterson, Hydrologist, U.S. Geological Survey, assisted with implementation of the EMSI[1] GMS[2] modeling techniques.

Jim Cannia, Nebraska Department of Natural Resources, reviewed the model and model inputs regarding suitability for determining hydrologic connectivity of streams with the aquifer.

Marie Krausnick, Upper Big Blue Natural Resources District, provided assistance with GIS mapping.

Xun Hong Chen, Ph.D. and *Mark Burhach, Ph.D.*, University of Nebraska Conservation and Survey Division, provided Geoprobe electric logging, permeameter testing, and pump tests to estimate aquifer hydraulic conductivity and river bed conductance on the Platte River and Big Blue River.

Larry Cast, Geologist, reviewed test hole and irrigation well drilling logs to determine geologic and hydrologic properties of the layers used to define the aquifer.

Rich Kern, P.E., Hydrologist / Programmer, Nebraska Department of Natural Resources, provided computer programming of utilities to assist with database management, grouping geologic layer parameters, retrieving data from the DNR databases, and analysis of GMS - MODFLOW outputs.

COHYST Modelers[3], developed the COHYST Eastern Regional groundwater model from which this sub-regional model is derived.

---

[1] EMSI is an acronym for “Environmental Modeling Systems, Inc.”

[2] GMS is an acronym for “Groundwater Modeling System”.

[3] COHYST is an acronym for “ Cooperative Hydrology Study”.

AUTHORIZATION

The groundwater model discussed in this report was commissioned by the Upper Big Blue Natural Resources District for the purpose of estimating the location of areas within the Natural Resources District that have the potential to be hydrologically connected to base-flow streams. The groundwater model and modeling results, shown in this report, have been presented to the Natural Resources District Board, and have been approved for submittal to the Nebraska Department of Natural Resources.

HGE
Hemenway Groundwater Engineering, Inc.

September 29, 2005

NE-0010-05

Mr. Jay Bitner
District Engineer
Upper Big Blue Natural Resources District
105 Lincoln Avenue
York, NE 68467

Dear Jay:

Subject: Groundwater Model Review for the Upper Big Blue Natural Resources District (UBBNRD)

As you requested, Hemenway Groundwater Engineering, Inc. (HGE) is pleased to submit this letter documenting the consulting services provided for the UBBNRD regarding your ongoing groundwater model development. HGE's Scope of Work (SOW) for consulting services was related to the review of the current groundwater computer model for the UBBNRD. The model is a sub-regional model of the area covered by the Eastern Model Unit (EMU) developed by the Nebraska Cooperative Hydrology Study (COHYST). The model utilizes the Groundwater Modeling System (GMS) pre- and post-processor modeling system and the United States Geological Survey (USGS) finite difference model MODFLOW 2000. The grids in the model are 1,320 feet by 1,320 feet or 40 acres per model grid, which is a refinement of the COHYST EMU model grid size of 2,640 feet by 2,640 feet. The focus of the UBBNRD model is to determine the depletion to the Platte River from wells, which represents 10 percent flow from the river after 50 years of well pumping. To determine the depletions, a baseline transient model was run without any wells pumping. Following the baseline run, the model was run numerous times with one well pumping at a new location at each model run. The depletions were calculated after each model run as a function of the distance of the well from the Platte River, and the 10 percent depletion line was mapped.

The services provided by HGE included reviewing the current UBBNRD groundwater model for "fatal flaws" and providing recommendations for improving and modifying the model to meet the intended purposes by the UBBNRD. HGE's recommendations were accepted and implemented by UBBNRD in the current groundwater model. The UBBNRD provided additional studies and information, model refinements, and improvements to the current COHYST EMU groundwater model. With these revisions and improvements, the current UBBNRD groundwater model meets the industry standards for groundwater modeling practices.

17011 Lincoln Avenue, PMB 416
Parker, Colorado 80134
Phone: 303-805-1750
Fax: 303-805-1850
EMAIL:
CHEMENWA@SNI.NET

HGE looks forward to the opportunity to work with you and the UBBNRD in the future. If you have any questions regarding this letter or HGE's review of the UBBNRD groundwater model, please do not hesitate to contact me.

Sincerely,

Hemenway Groundwater Engineering, Inc.

Courtney Hemenway
President

HGE/UBBNRDGWMODELREVLET

TABLE OF CONTENTS

INTRODUCTION 1

PURPOSE 1

CONCEPTUAL MODEL 1

GEOLOGIC AND HYDROSTRATIGRAPHIC UNITS 4

MODEL DESCRIPTION 5
- Model Grid 5
- Modules 5
  - River Module 5
  - Well Module 6
  - Recharge Module 7
  - Evapotranspiration Module 7
- Boundary Conditions 8
- Model Flow Simulation 9
- Flow Equation Solver 9
- Aquifer Characteristics 10
  - Hydraulic Conductivity K_x 10
  - Anisotropic Ratios 11
  - Specific Yield S_y 11
  - Specific Storage Ss 11

PRE-DEVELOPMENT PERIOD 12
- Mean Difference 13
- Mean Absolute Difference 13
- Root Mean Square Difference 13

PRE-DEVELOPMENT MODEL - WITHOUT PUMPING 14

HYDROLOGICALLY CONNECTED AREA 15
- 10% / 50-Year Boundary Determination 18

INTRODUCTION

This report discusses development and application of a groundwater model for a region that lies within the boundary of the Cooperative Hydrology Study (COHYST) eastern regional groundwater model[4] in Nebraska. The geographic area modeled is shown on Figure 1 and includes all, or portions of, Platte, Polk, York, Nance, Merrick, Hamilton, Clay, Nuckolls, Howard, Hall, and Adams Counties. The modeled area overlays portions of the Upper Big Blue, Central Platte, and Little Blue Natural Resources Districts. The total land surface within the model boundary is approximately 7,520 square miles (4.8 million acres).

PURPOSE

The purpose of this model is to provide a method for calculating the potential increase in the rate of flow from the Platte River to the underlying aquifer due to groundwater pumping near the Platte River within the Upper Big Blue Natural Resources District. The model is used to define a boundary encompassing the area within which a well pumping groundwater could increase flow from the Platte River to the underlying aquifer by an amount equal to, or greater than, 10 percent of the volume pumped over a period of 50 years. For purposes of determining whether or not a river basin is *fully appropriated* [5], the Nebraska Department of Natural Resources considers that wells within the 10 percent / 50-year boundary are hydrologically connected to the river.

CONCEPTUAL MODEL

The model boundaries are defined with a series of *fixed flow* arcs that specify flow into or out of the model, depending upon the direction and slope of the groundwater gradient at the boundary. The Platte River is defined with a series of *river* arcs which specify the river bed conductance, river bed thickness, and river stage. The model cells intersected by the river arcs are defined by the model as a series of point source river cells, each with its own conductance value. The model cells intersected by the fixed flow boundary arcs are defined by the model as a series of wells that are either source (injection) or sink (withdrawal), depending on whether the

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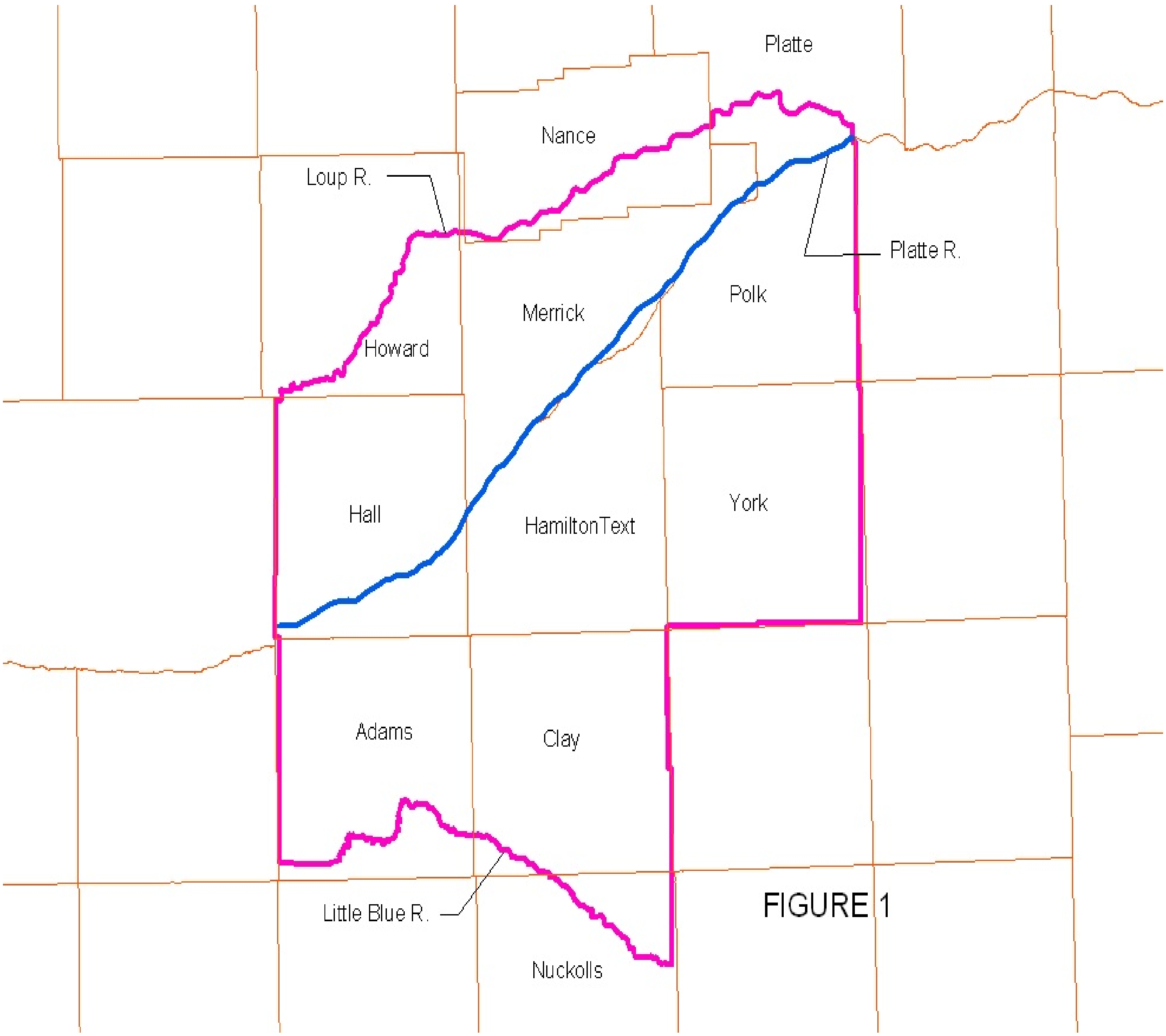
4 S. M. Peterson, *Groundwater Flow Model of the Eastern Model Unit of the Nebraska Cooperative Hydrology Study (COHYST) Area*, 2005.

5 Nebraska Department of Natural Resources, Proposed Rule pursuant to Neb. Rev. Stat. §46-713.


Platte
Nance
Loup R.
Platte R.
Polk
Merrick
Howard
Hall
HamiltonText
York
Adams
Clay
Little Blue R.
Nuckolls
FIGURE 1

boundary flow is into or out of the model at that point. The amount of river to aquifer flow induced by pumping is tested with a single well, which is moved from cell to cell parallel to the Platte River, at varying distances from the river. Other streams within the model boundary, such as the Big Blue River and its tributaries, including the West Fork Big Blue River, Lincoln Creek, and Beaver Creek, are not included in the model. The bed conductances of these rivers and streams are very low, approximately 0.0079 ft^2/day, and have minimal connectivity to the underlying aquifer[6] and the Platte River. Areal sources and sinks included in this model are recharge from precipitation, and evapotranspiration from rooted plants located in wet meadows near the Platte River. The model geology is represented by five unconfined layers. The numerical flow model is based on the following basic assumptions:

- At the scale in which this model is constructed, flow in the aquifer obeys Darcy's Law and mass and energy are conserved.
- Since the modeled fluid is groundwater, having a temperature in the range of 50 degrees Fahrenheit, the density and viscosity of water are constant over time and space.
- Parameters are uniform within each cell, and represent an estimate of their average value within the cell.
- The interchange of water between the aquifer and Platte River can be adequately simulated as one-dimensional flow through a discrete streambed layer. This conceptualization is appropriate over the scale at which this model is constructed.
- Hydraulic conductivity in the horizontal plane is isotropic; however, hydraulic conductivity in the vertical direction is not equal to hydraulic conductivity in the horizontal direction. The horizontal to vertical anisotropic ratio is assigned a value of 10 (i.e. horizontal hydraulic conductivity is ten times greater than vertical hydraulic conductivity), unless otherwise noted.

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[6] Xun Hong Chen, *River Bed Conductance Studies - West Fork Big Blue River and Platte River in Nebraska*, University of Nebraska Conservation and Survey Division, 2005.

GEOLOGIC AND HYDROSTRATIGRAPHIC UNITS

The model has five unconfined geologic layers. The layer definitions are consistent with those documented in the COHYST aquifer characterization report[7]. The model layers consist primarily of Quaternary deposits of Pleistocene alluvium, Pleistocene and Holocene loess, Holocene dune sand, and Holocene valley fill. Valley fill deposits are found along the Platte River and consist of gravel, sand, and silt. Alluvial deposits, which typically support high capacity wells, are found throughout the model area. In topographic bedrock highs these deposits are generally thinner, and produce lower yielding wells. Loess deposits are found throughout the model area, and the thickest deposits are located along the Platte River bluffs. The deposits become thinner as they approach the Platte River north of the loess bluffs. The Platte River bed contains a low permeability loess layer at about 10 to 20 feet below the current streambed surface[8]. The bedrock formation at the bottom of Layer 5 consists of shale, chalk, limestone, siltstone, and sandstone of Cretaceous age. These bedrock materials transmit very little water, and for modeling purposes are considered to be impermeable.

The model layers are numbered 1 through 5. Unit 1 is the top layer, and Unit 5 is the bottom layer. The layers used in this model are described as follows:

- Layer 1 Top layer consisting of upper Quaternary age silt and clay with some sand and gravel
- Layer 2 Middle Quaternary age sand and gravel
- Layer 3 Lower Quaternary age silt and clay with some sand and gravel
- Layer 4 Upper Tertiary age silt and clay with some sand and gravel
- Layer 5 Middle Tertiary age sand and gravel underlain with bedrock materials consisting of shale, chalk, limestone, siltstone, and sandstone

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7 J. C. Cannia, D. Woodward, L. Cast, and R. L. Luckey, Cooperative Hydrology Study COHYST Hydrostratigraphic Units and Aquifer Characterization Report, November 2004.

8 See geoprobe electric logs shown in Appendix B

MODEL DESCRIPTION

The groundwater model is a three-dimensional finite difference computer model developed around the MODFLOW[9], Version 2000, groundwater modeling software enclosed within EMSI GMS[10], Version 5.1. The GMS software includes a pre-processor to read input data and place it in the model according to MODFLOW format requirements. GMS also does some post-processing of output in both graphical and numerical forms. The units of measure used in this model include feet for linear measure, days for time, feet per day for velocity, cubic feet for volume, and cubic feet per day for flow rate.

Model Grid

The model grid has 120,330 cells per layer. Each cell measures 1,320 feet per side, and covers an area of approximately 40 acres. Model feature locations are geo-referenced in the horizontal plane to the Nebraska State Plane Coordinate System, NAD 83 - feet. Top and bottom elevations of each layer are referenced to USGS mean sea level datum.

Modules

The MODFLOW software is modular in the sense that various modules (packages) can be activated for any particular modeling situation. The modules used in this model include river, well, recharge, and evapotranspiration.

River Module

The Platte River is simulated in this model as a series of arcs, connected at their upstream and downstream ends at nodes, with a combined length of 87.8 miles. Attributes associated with the arcs and nodes specify the river bed conductance, bottom of river bed elevation, and river stage. The hydrologic properties (K, S_y) of model cells identified as river cells (cells crossed by river arcs), and located in Layer 1, are adjusted to match the hydrologic properties of the underlying cell in Layer 2. In this way there is a direct connection of the Platte River bed to the aquifer, and the only limitation on inter-connectivity between the river bed and underlying

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[9] M. G. McDonald and A.W. Harbaugh, *Modular Three-Dimensional Finite-Difference Groundwater Flow Model*, U.S. Geological Survey, 1984.

[10] *Groundwater Modeling System (GMS)*, Environmental Modeling Systems, Inc. (EMSI), Park City, Utah.

aquifer is river bed conductance. River bed conductance is a function of river bed length, width, bed thickness, and hydraulic conductivity. MODFLOW uses the following equation[11] to calculate bed conductance:

EQ. 1 $$C = (k \times L \times W) / M$$

For each river arc "n":

C_n = streambed conductance ($ft^2/d/ft$)

k_{vn} = vertical hydraulic conductivity of the streambed (ft/d)

L_n = length of the streambed (ft)

W_n = width of streambed (ft)

M_n = thickness of streambed (ft)

For this model, the value of river bed conductance at each river arc is set at the same value as used in the COHYST Eastern Regional Model, except where detailed testing indicates the value should be different. The values established by testing were determined based on geoprobe and permeameter tests conducted by the University of Nebraska Conservation and Survey Division. Geoprobe electric logs, hydraulic conductivities, and bed conductance calculations are shown in Appendix B of this report. Platte River bed conductances used in this model are set at 11 $ft^2/d/ft$ in reaches where testing is completed. River bed conductances in the remaining reaches vary from 20 $ft^2/d/ft$ to 30 $ft^2/d/ft$.

Well Module

The potential increase in induced flow from the Platte River to the underlying aquifer, due to groundwater pumping near the Platte River, is tested with this model by placing a simulated pumping well at alternate cell locations, operating the model for a 50-year period at each location, and calculating the change in the water budget when compared with the baseline condition. The initial baseline condition is simulated with no pumping well.

For these simulations, pumping is assumed to be from Layer 2, the volume of water

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11 *Documentation of a Computer Program to Simulate Stream-Aquifer Relations Using a Modular, Finite Difference, Groundwater Flow Model*, U.S. Geological Survey, Open-File Report 88-729, 1989.

pumped is set at 160 acre-feet per year, and the pumping rate is set to be continuous at 19,094.79 cubic feet per day. This volume of groundwater is approximately the average amount of water pumped in one year to irrigate a quarter section of crop. A gravity irrigated system would pump slightly more volume on average, and a pivot irrigated system would pump slightly less volume on average, based on the District's records of irrigation water use. Although irrigation systems typically operate at a higher pumping rate, are operated on an intermittent pumping schedule, and only operate for a few months per year, a continuous lower pumping rate is used to simplify the modeling process. The volume of water pumped per year would be the same with either continuous or transient pumping schedules. The continuous pumping schedule is not expected to give significantly different results than a transient pumping schedule would yield. Some comparisons of continuous and transient pumping were made to confirm this conclusion.

<u>Recharge Module</u>

Recharge is modeled as an areal source of inflow to the aquifer, and includes the amount of precipitation that percolates from the surface through Layer 1 into Layer 2. The recharge rate used in this model, in feet per day, is interpolated from the COHYST Eastern Model, pre-development period, scatter point data set. The scatter point file is derived from the COHYST EMU model and interpolated to this model's 2-dimensional grid. The 2D data set is imported to the MODFLOW model recharge array. The recharge point of application option is set to the highest active layer at each grid cell. For this model, the minimum recharge rate is 0.000222 feet per day (0.97 inches per year), and the maximum rate is 0.000557 feet per day (2.44 inches per year). The mean rate is 0.000222 feet per day (0.972 inches per year). The recharge rate is held constant throughout the modeled time period, and does not vary from stress period to stress period.

<u>Evapotranspiration Module</u>

Evapotranspiration (ET) is modeled as the amount of groundwater extracted from the aquifer by rooted vegetation, and then evaporated from the plant canopy to the atmosphere external from the model. For this model ET is considered to be an areal sink; i.e., outflow from the model space. The ET rate data set used in this model is interpolated from the COHYST Eastern Model pre-development data set. A scatter point file is produced from the COHYST

EMU model and interpolated to this model's 2-dimensional grid. The 2D data set is then imported to the MODFLOW model ET array. The point of ET withdrawal is the top of Layer 1, and the extinction depth is set at a specified depth (nominally 7 feet) below the top of Layer 1. For this sub-regional model, the minimum ET rate is 0.00 feet per day, and the maximum rate is 0.002993 feet per day (13.1 inches per year). The rate of evapotranspiration is held constant throughout the modeled time period, and does not vary from stress period to stress period.

Wetland areas, mostly located near the Platte River, are treated as groundwater sinks, where groundwater can be removed from the model space by plant evapotranspiration. The evapotranspiration rate, extinction depth, and active ET layer are interpolated to the model 2D grid from COHYST EMU scatter point data sets. Areas that have potential for significant evapotranspiration are selected using 1997 land use mapping data for wetlands (Dappen and Tooze, 2001), and also by defining areas where the depth to groundwater is on average 7 feet or less below land surface, according to USGS long-term depth to water data (U.S. Geological Survey National Water Information System, 1999).

Boundary Conditions

The model is bounded vertically by land surface at the top of Layer 1 and bedrock at the bottom of Layer 5. The model is bounded horizontally by fixed flow boundaries. A fixed flow boundary is a boundary where the flow is specified prior to the simulation and held constant throughout the simulation (McDonald and Harbaugh, 1988). At fixed flow boundaries the simulated water level can change, but flow across the boundary does not change. The northern model boundary is aligned with the Loup River and the southern boundary is aligned with the Little Blue River and southern boundary of Adams County. The eastern model boundary is aligned with the eastern boundaries of York and Polk Counties, and the western boundary is aligned with the western boundaries of Hall and Adams Counties, as shown on Figure 1. The rate of flow through each model boundary, in cubic feet per day, is calculated using the Darcy Equation.

EQ. 2 $$Q_n = k_n \times i_n \times A_n$$

For each boundary arc "n"

Q_n = fixed rate of flow through the boundary, ft^3/d

k_n = weighted horizontal hydraulic conductivity, ft/d

i_n = gradient of the 1950 groundwater surface perpendicular to the boundary flow plane, ft/ft

A_n = cross sectional area of the flow plane at the boundary, ft^2

Each layer's thickness determines the relative weight given to each layer's hydraulic conductivity for this calculation. The calculated boundary flow is distributed evenly over the saturated thickness between the groundwater level and the base of the aquifer at each boundary arc. Appendix A contains calculations and supporting documents used to compute boundary fixed flows. A boundary flow is not computed for Layer 1, since it is a silty clay layer generally representing the unsaturated zone which overlays the saturated zone.

Model Flow Simulation

The MODFLOW software has several packages (BCF, LPF, and HUF) available for calculating conductance coefficients and groundwater storage parameters to be used in the finite-difference equations that calculate flow between cells. The Layer Property Flow (LPF) package is selected as the internal flow calculation methodology for this model. The LPF package reads input data for hydraulic conductivity and global top and bottom elevation data for each cell (layer). Transmissivity is calculated for each cell at the beginning of each iteration of the flow equation matrix solution process. The LPF package calculates leakance between layers using the vertical hydraulic conductivity, based on estimated anisotropic ratio K_x/K_z, and distance between nodes obtained from global elevation data.

Flow Equation Solver

The MODFLOW software has several linear differential equation "solver" packages (SIP1, PCG2, SCR1, and GMG) available. For this model, the pre-conditioned conjugate-gradient[12] (PCG2) package is selected to solve the linear finite difference equation matrix. For a transient groundwater model, the solution matrix is expressed as shown in EQ. 3, where [A] is the coefficient matrix, [x] is a vector of hydraulic heads, and [b] is a vector of defined flows, associated with head-dependent boundary conditions and storage terms at each grid cell.

EQ. 3 $$[A] \bullet [\vec{x}] = [\vec{b}]$$

The matrix is solved iteratively until both head-change and residual convergence criteria are met. The convergence criteria are too large if the global groundwater flow budget discrepancy is unacceptably large. In general, a global budget discrepancy less than one percent is considered acceptable. Convergence criteria for this model, specified in the input options for the PCG2 module, are 0.5 foot for heads and 10.0 ft^3/d for flow residual. The iteration parameters are not specified, but rather are calculated internally.

Aquifer Characteristics

Aquifer properties are input for each layer, including horizontal hydraulic conductivity (K_x), vertical anisotropic ratio (K_x/K_z) or vertical hydraulic conductivity K_z, horizontal anisotropic ratio (K_x/K_y), Specific Storage (S_s), and specific yield (S_y). The procedures used to estimate parameter values for each layer are described in the COHYST hydrostratigraphic Units Characterization Report[13].

<u>Hydraulic Conductivity K_x</u>

Test well logs, interpreted by Reed and Piskin[14], are the basis for horizontal hydraulic conductivity values used in this groundwater model and the COHYST eastern regional model. The interpreted values for each layer are weighted according to layer thickness, and the weighted average value of K_x is then determined for each model layer at each test well location. The

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12 P. Concus, G. H. Golub, and D. P. O'Leary, A Generalized Conjugate Gradient for the Numerical Solution of Elliptical Partial Differential Equations, Academic Press, 1976.

13 J. C. Cannia, D. Woodward, L. Cast, and R. L. Luckey, *Cooperative Hydrology Study COHYST Hydrostratigraphic Units and Aquifer Characterization Report*, November 2004.

14 E. C. Reed and R. Piskin, unpublished report, University of Nebraska Conservation and Survey Division.

process used to weight the values is written in a computer code called *Geoparm*[15]. A 2D data set is then created by interpolating the computed values. The 2D data set is then used to set the MODFLOW array of values for each layer.

Anisotropic Ratios

As described previously in this report, the vertical anisotropic ratio, K_x/K_z , is estimated to be 10.0 for all layers at each grid cell, unless pump testing indicates a different ratio, and the horizontal anisotropic ratio, K_x/K_y, is estimated to be 1.0.

Specific Yield S_y

Data compiled by USGS, and summarized by Reed and Piskin, is the basis for specific yield values used in this groundwater model and the COHYST eastern regional model. As discussed in the Hydrostratigraphic Units Report, specific yield values are interpreted for each layer material classification. The interpreted values are then weighted using the Geoparm program to establish specific yield for each model layer at each test well location. The computed values are then interpolated to the model's 2D grid for each model layer. The 2D data sets are then used to set the MODFLOW array values for each layer.

Specific Storage Ss

All layers in this model are considered to be unconfined; however, the LPF simulation options available in MODFLOW are either confined or convertible. The convertible option is selected for all layers, and the specific storage for all layers, except Layer 1, is set to $2.1e^{-3}$; this value is based on discussions with UNL Conservation and Survey[16] and takes into account low potential for changes in aquifer storage due to height of overburden or changes in hydraulic head. The specific storage for Layer 1 is set to 0.16, the estimated specific yield, since this layer is always unconfined, and cannot be converted to confined.

Specific storage is the volume of water per unit volume of *confined* saturated aquifer that is absorbed, or expelled, due to changes in pressure within the aquifer. Overburden tends to

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15 R. Kern, *Nebraska Cooperative Hydrology Study Computer Program Documentation GeoParam - Hydraulic Conductivity from Well Logs*, Nebraska Department of Natural Resources.

16 Personal communication with Xun Hong Chen, University of Nebraska, Conservation and Survey Division.

consolidate the aquifer (reduce storage volume), and hydraulic pressure head tends to offset consolidation (increase storage volume).

Storativity for a *confined* layer is equal to the product of specific storage and layer thickness. Storativity for an *unconfined* layer is equal to the specific yield plus the product of groundwater depth and specific storage.

PRE-DEVELOPMENT PERIOD

Geologic and hydrogeologic layer parameters used in this model are derived from calibrated COHYST eastern regional model (EMU) data. The EMU was calibrated for the pre-groundwater development period by varying and adjusting evapotranspiration, recharge, hydraulic conductivity, properties at horizontal flow boundaries, and streambed conductances. For this model the evapotranspiration, recharge and horizontal hydraulic conductivity are interpolated from EMU scatter point files. Streambed conductances and vertical hydraulic conductivities are adjusted at some locations based on recent testing conducted by the University of Nebraska Conservation and Survey. Fixed flows at boundaries are computed for each boundary arc as previously described. Observed water levels, measured between 1946 and 1955, are used to establish the starting head values.

Observed water levels used to establish starting heads are from a period of relatively stable conditions. Observation points were selected as being representative of pre-groundwater development, and only the most reliable data within 4-mile by 4-mile grid cells were selected (by COHYST modelers) for EMU calibration. This selection process prevents a cluster of closely spaced observation wells from dominating the calibration process. After screening values in all of the 4 by 4-mile cells, a few points that appeared to have large errors in location or land-surface elevation were excluded from the calibration data set. The starting heads file for this model is based on a sub-set of the EMU calibration data set that contains 209 of the observation points.

The ability of this model to represent a 50-year period of pre-groundwater development conditions is evaluated by comparing the percent discrepancy in global groundwater flow budget, as well as the mean difference, mean absolute difference, and root mean square of the differences between observed pre-development groundwater levels at the beginning and end of a 50-year computer run without well development.

Mean Difference

The mean difference (MD) of observed and simulated water levels is defined in EQ.4. The variable h_0 is the observed water level and h_s is the simulated water level at each of the n observation points. The mean difference is used here as a measure of overall bias in calibration, and as such should be close to zero at calibration.

EQ.4 $$MD = \frac{1}{n}\sum_{i=1}^{n}\left(h_0 - h_s\right)_i$$

Mean Absolute Difference

The mean absolute difference (MAD) of observed and simulated water levels is defined in EQ.5. The MAD is used here to evaluate the overall model calibration, since positive and negative differences do not cancel each other. All differences are given an equal weight, so a few measurements with large differences will not dominate the result.

EQ.5 $$MAD = \frac{1}{n}\sum_{i=1}^{n}\left|h_0 - h_s\right|_i$$

MODFLOW calculates the water level changes as draw-downs, therefore positive changes are declines and negative changes are rises.

Root Mean Square Difference

The root mean square difference (RMSD), also referred to as the quadratic mean, is defined in EQ. 6. This statistic is the standard deviation of the differences between observed groundwater levels and groundwater levels produced by the model, for the pre-development period. Assuming that the differences between observed and modeled water levels are normally distributed about the mean difference, the standard deviation gives a measure for determining the range within which the differences can be expected to occur. Statistically, 68.27% of the differences are expected to occur within MD ± RMSD, and 95.45% of the differences are expected to occur within MD ± (2)(RMSD).

EQ. 6 $$RMSD = \left[\frac{1}{n}\sum_{1}^{n}\left(h_s - h_0\right)_i^2\right]^{0.5}$$

PRE-DEVELOPMENT MODEL - WITHOUT PUMPING

Starting heads for the pre-development model are obtained by interpolating the observed pre-development water levels to the model 2D grid, which is then imported to the MODFLOW model starting head data set. The observation data points are also imported to the model so that heads computed by the model can be compared to the starting heads for the purpose of evaluating groundwater level changes over the 50-year period. Figures 2 and 3 show the locations of water level observation points, water level contours, and statistical variation at each observation point for the starting heads and 50-year model run. Statistical variations are shown in 10 feet increments; green indicates variation from 0 to 10 feet, yellow indicates variation from 10 to 20 feet, and red indicates variation from 20 to 30 feet. If the indicator is above the line, the computed water level is higher than observed, and if the indicator is below the line the computed water level is lower than observed at that observation point. The mean difference between observed and interpolated water levels, for both starting heads and 50-year model run, is 0.240 feet, the mean absolute difference is 1.376 feet, and the root mean square difference is 2.235 feet. Statistically it can be expected that approximately 95% of the differences between observed and computed water levels will occur within ± 2.235 feet of the mean difference.

The global groundwater inflow and outflow budgets, without well development, are shown in Tables 1 and 2 for the 50-year model run.

TABLE 1

MODEL INFLOW VOLUMETRIC BUDGET

Inflow From	Inflow Volume (KAF)	Inflow Rate (KAF / Yr.)	Percent of Inflow (%)
Storage	19,088	382	52.1
Fixed Flow Boundary	2,324	46	6.4
Platte River	4,388	88	12.0
Recharge	10,781	216	29.5
Total Inflow	36,580	732	100

TABLE 2

MODEL OUTFLOW VOLUMETRIC BUDGET

Outflow From	Outflow Volume (KAF)	Outflow Rate (KAF / Yr.)	Percent of Outflow (%)
Storage	22,196	444	60.7
Fixed Flow Boundary	5,599	112	15.3
Platte River	106	2	0.3
Evapotranspiration	8,681	174	23.7
Total Outflow	36,582	732	100

For the 50-year no well development scenario, the model calculates flow from the Platte River to the underlying aquifer at an average rate of 86 acre-feet per year within the model boundaries. This river to aquifer flow, without pumping, is the baseline for computing induced river to aquifer flow due to groundwater pumping. The global groundwater flow budget discrepancy is less than 0.01 percent.

HYDROLOGICALLY CONNECTED AREA

The portion of the Upper Big Blue Natural Resources District that is considered to be "hydrologically connected" to the Platte River, is that area contained between the Platte River, the Upper Big Blue NRD boundary, and the 10% / 50 year line. Groundwater pumping wells contained within this area are determined by the model to have the potential for inducing additional flow from the Platte River to the underlying aquifer by an amount of at least 10 percent of the volume pumped over a 50-year period. The increase in flow from the river to the aquifer is presented in terms of the "global" model volumetric budget; i.e., the water pumped from the well causes an increase in the mass of water moving from the river to the aquifer, but does not address the transport issues, such as source path or age of water pumped.

A baseline model run, without a pumping well, establishes the volume of water moving from the river to the aquifer due to non-pumping gradients. Independent model runs are then made for each new location of the single pumping well. The well is placed at the center of a grid

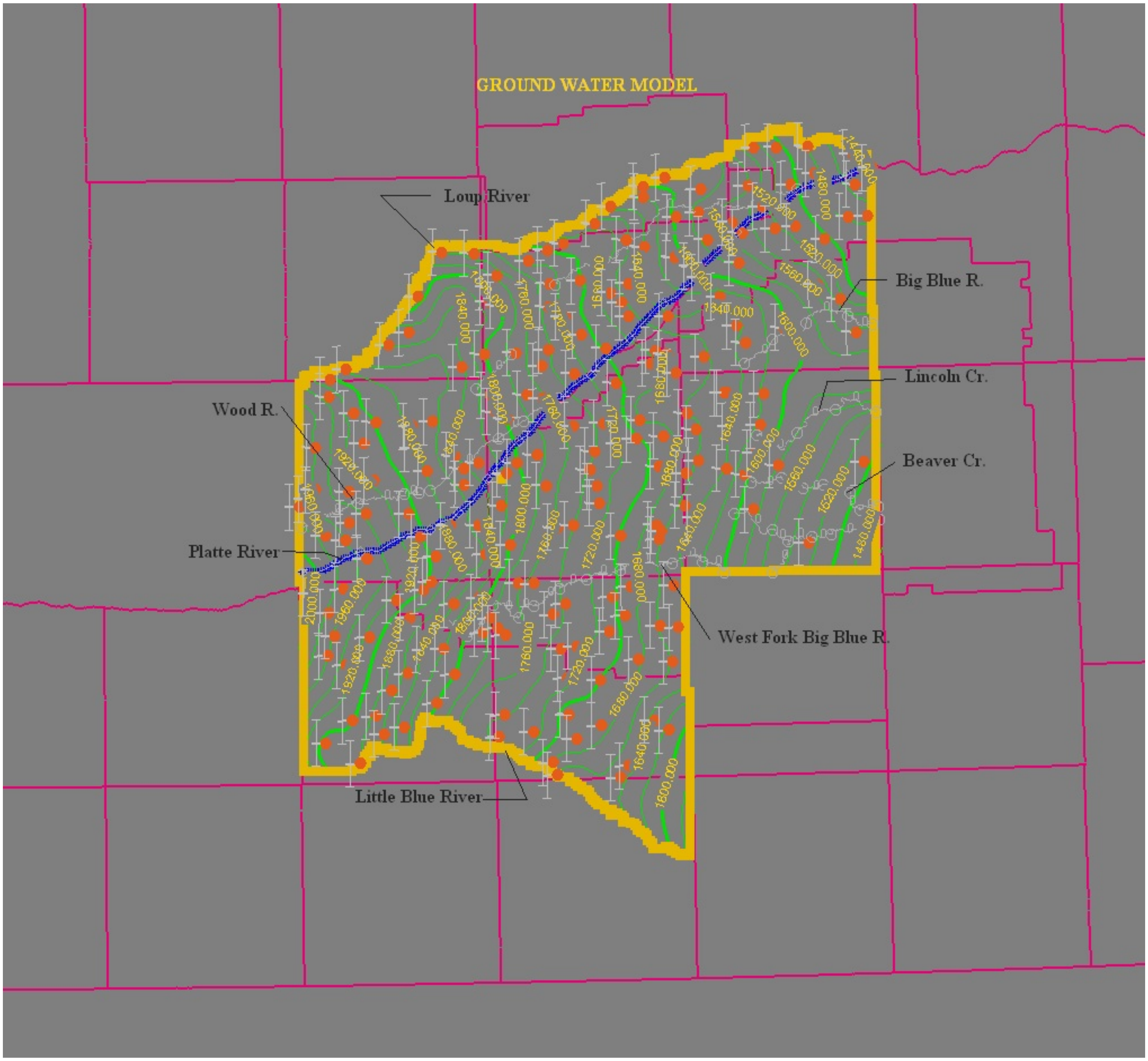


FIGURE 2

PRE-DEVELOPMENT G.W. LEVELS

STARTING HEADS

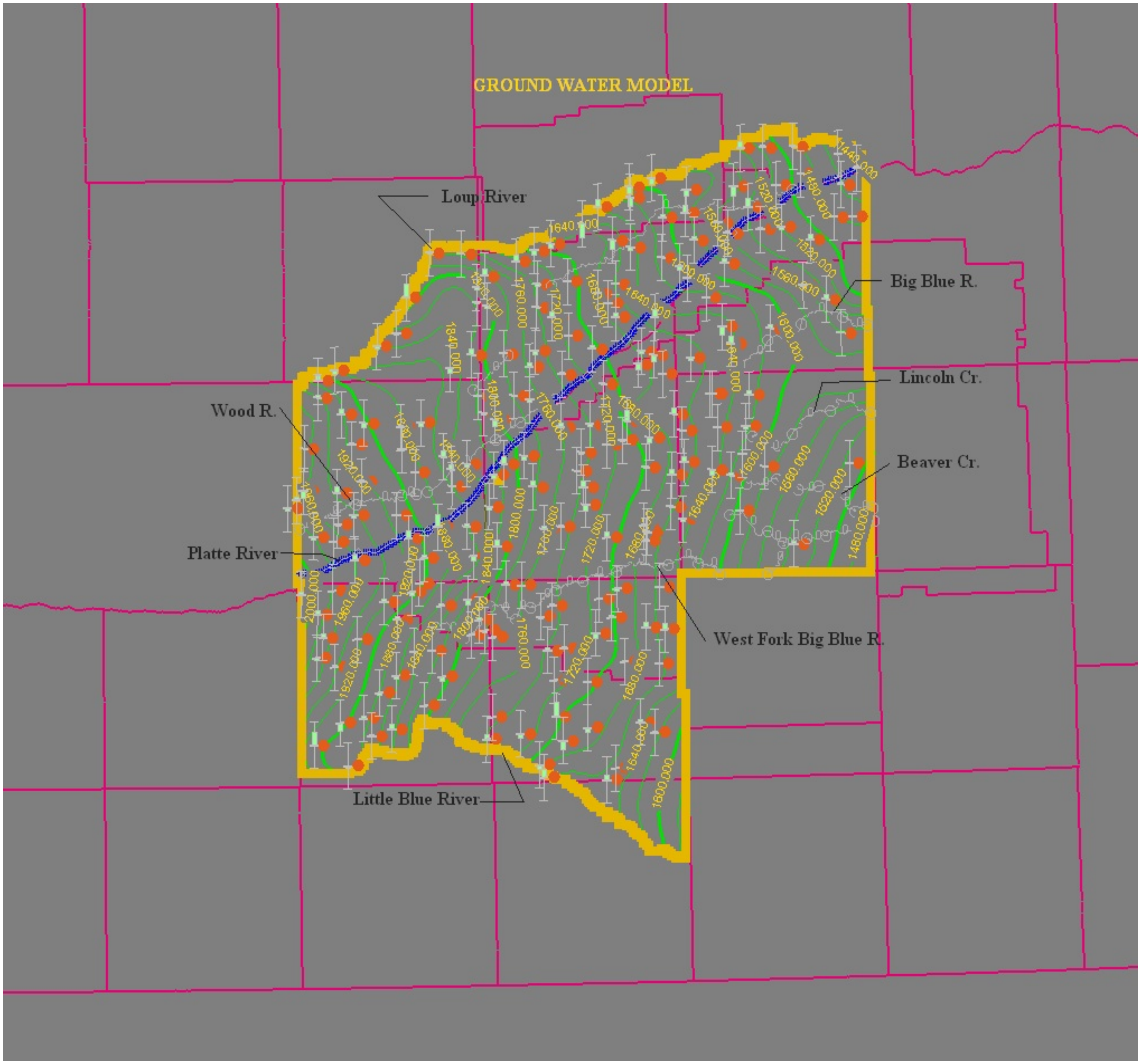


FIGURE 3

FIFTY YEAR MODEL G.W. LEVELS

CHANGES AT OBSERVATION WELLS

cell, and the well screen is assumed to be in Layer 2 for each run. The global volumetric budgets at the end of the 50th stress period are compared with and without pumping, and the difference in river flow into the model is used to determine the volume of water induced from the river to the aquifer due to pumping.

10% / 50-Year Boundary Determination

The 10% / 50-year boundary is determined by evaluating groundwater pumping along transects, spaced approximately 1 mile apart and perpendicular to the Platte River. Transect cells that lie on either side of the boundary line are interpolated linearly to determine the actual coordinates[17] of the boundary line on each transect. Table 3 is a summary of coordinates used to establish the 10 / 50 boundary line within the Upper Big Blue NRD. Figures 4 and 5 are graphical representations of the 10% / 50-year boundary line location.

TABLE 3

10% / 50-YEAR BOUNDARY WITHIN THE UPPER BIG BLUE NRD

STATE PLANE COORDINATES

Easting	Northing
2115914.5307	368243.7495
2119524.3678	373861.1446
2122067.5150	377912.3125
2124670.4467	383220.1545
2128158.4452	387639.9242
2132229.2680	391476.8695
2135624.8026	395989.1030
2139012.1417	400512.5376
2140957.5416	402519.5190
2145105.3989	406279.4298
2149493.4078	411118.6532
2153212.8089	415307.0203

17 Coordinate system is North American Datum, 1983, Nebraska State Plane, Feet.

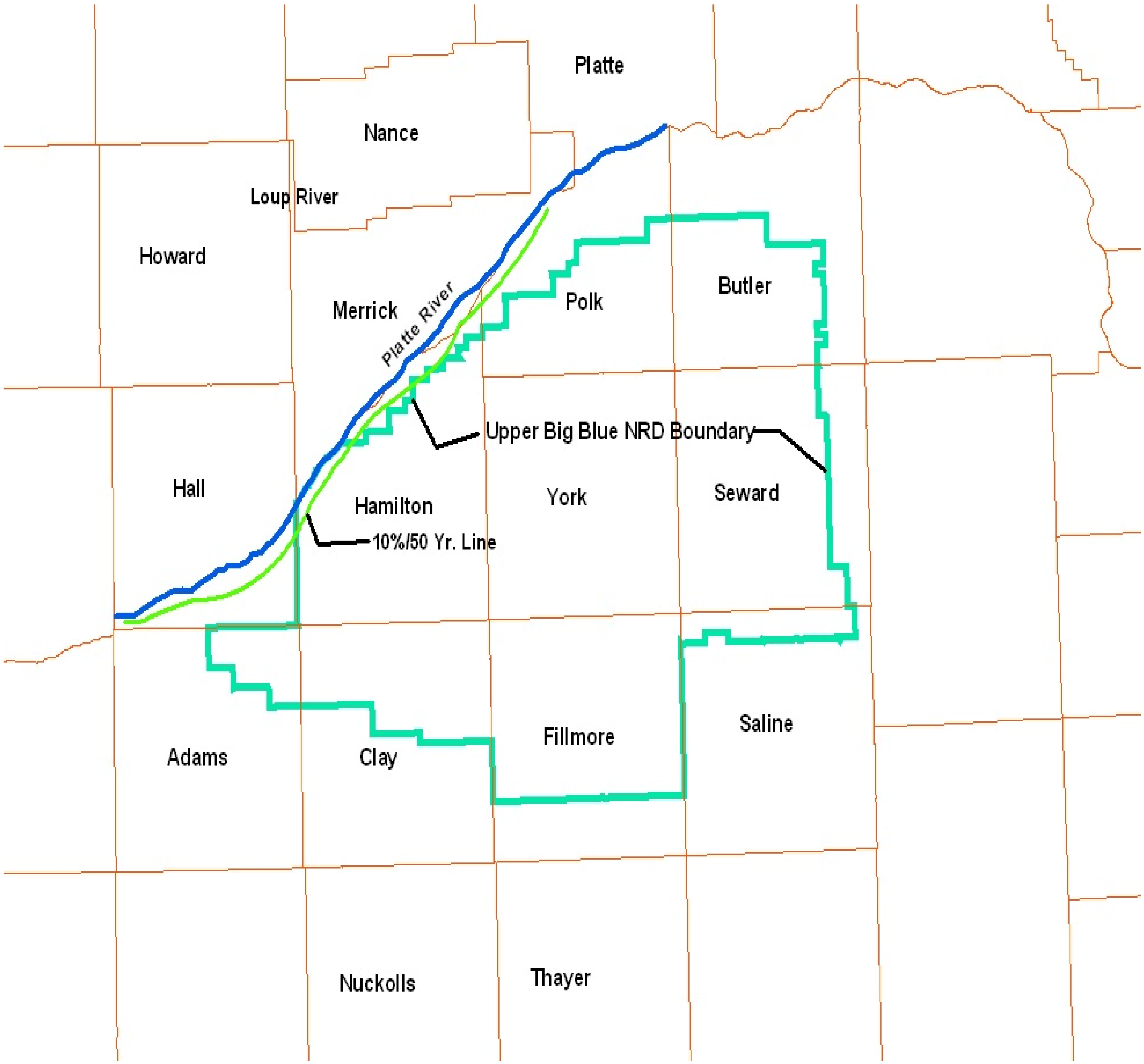


FIGURE 4

10% / 50-YEAR LINE PLATTE RIVER

HALL, HAMILTON AND POLK COUNTIES

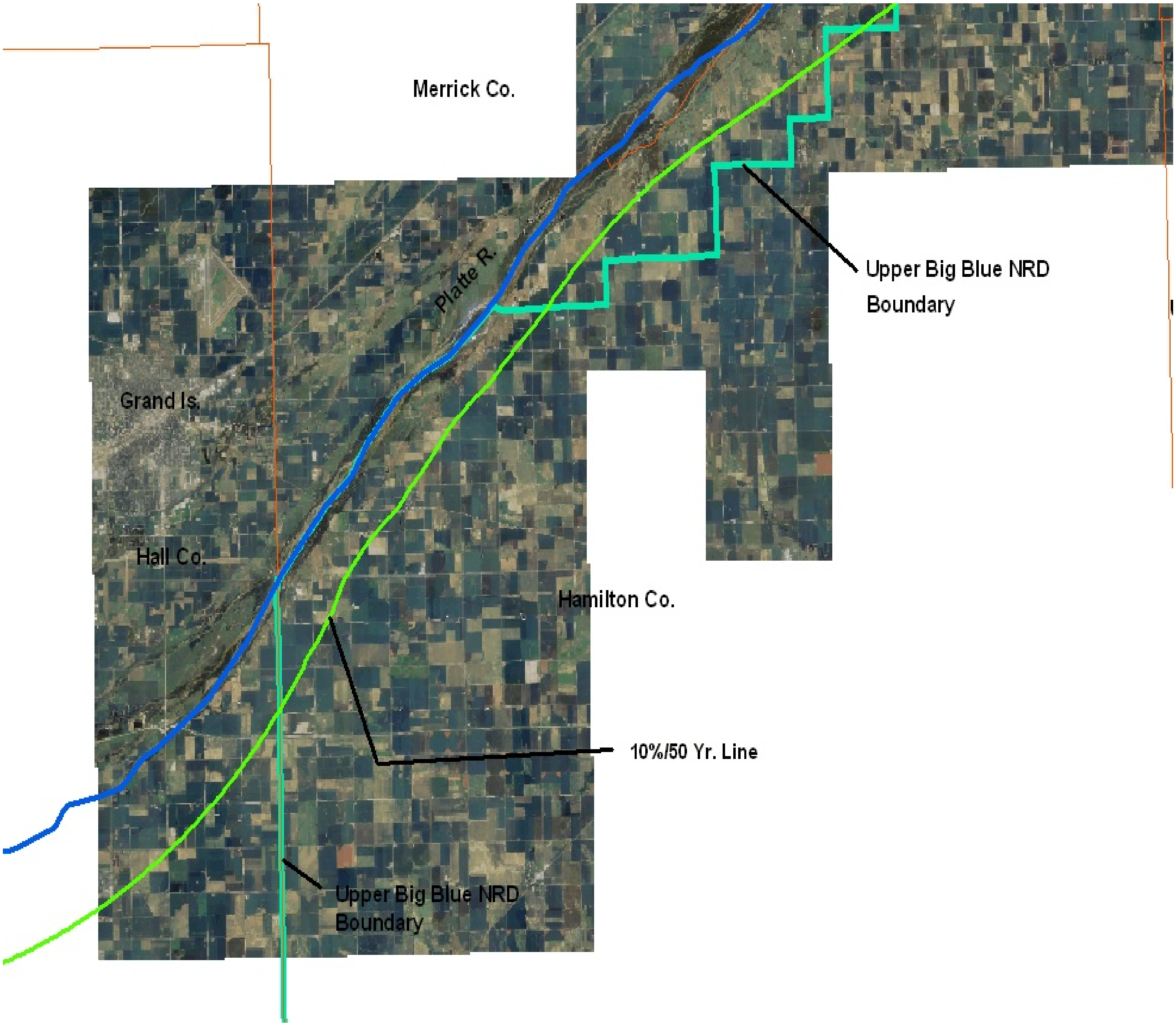


FIGURE 5

10% / 50-YEAR LINE PLATTE RIVER

WITHIN THE UPPER BIG BLUE NRD BOUNDARY

APPENDIX A
MODEL BOUNDARY
FIXED FLOW CALCULATIONS

Ground Water Model
Fixed Flow Boundary Estimates
Southern Boundary
1950 G.W. Level - Layer 5
Updated 07/18/05

Boundary Arc No.	Gradient Crossing Boundary (ft./ft.)	Gradient Angle At Boundary (deg)	Gradient Perpendicular To Boundary (ft./ft.)	Weighted Hyd. Cond. At Boundary (ft./d)	Weighted G.W. Velocity At Boundary (ft./d)	1950 Groundwater Elevation (ft.>msl)	Bottom Layer 5 Elevation (ft.>msl)	Saturated Thickness At Boundary (ft.)	Boundary Arc Length (ft.)	Boundary Flow Area (ft.2)	Boundary Flow (ft.3/d)
80	-0.000869	90	0.000000	44.3	0.000	1880.0	1660.4	219.6	46,017	10,105,333	0
38	-0.00208	90	0.000000	69.6	0.000	1833.0	1589.0	244.0	28,340	6,914,960	0
39	-0.00208	0	-0.002080	54.4	-0.113	1805.0	1557.6	247.4	27,847	6,889,348	-779,543
82	-0.00129	90	0.000000	59.8	0.000	1775.0	1551.3	223.7	41,096	9,193,175	0
23	-0.00089	90	0.000000	109.5	0.000	1740.0	1587.2	152.8	16,903	2,582,778	0
40	-0.000968	90	0.000000	84.0	0.000	1728.0	1600.4	127.6	30,987	3,953,941	0
41	-0.002924	72	-0.000904	144.8	-0.131	1680.0	1575.0	105.0	24,486	2,571,030	-336,384
1	-0.002000	35	-0.001638	192.1	-0.315	1650.0	1566.5	83.5	24,920	2,080,820	-654,872
42	0.001481	24	0.001353	93.3	0.126	1660.0	1562.9	97.1	35,838	3,479,870	439,268
43	0.002000	33	0.001677	82.0	0.138	1632.0	1467.0	165.0	35,201	5,808,165	798,866
36	0.002105	67	0.000822	94.2	0.077	1600.0	1410.6	189.4	31,263	5,921,212	458,766

Total Estimated 1950 Boundary Flow = -73,898

Ground Water Model
Fixed Flow Boundary Estimates
Northern Boundary
1950 G.W. Level - Layer 5
Updated 07/18/05

Boundary Arc No.	Gradient Crossing Boundary (ft./ft.)	Gradient Angle At Boundary (deg)	Gradient Perpendicular To Boundary (ft./ft.)	Weighted Hyd. Cond. At Boundary (ft./d)	Weighted G.W. Velocity At Boundary (ft./d)	1950 Groundwater Elevation (ft.>msl)	Bottom Layer 5 Elevation (ft.>msl)	Saturated Thickness At Boundary (ft.)	Boundary Arc Length (ft.)	Boundary Flow Area (ft.2)	Boundary Flow (ft.3/d)
79	-0.002609	54	-0.001534	34.9	-0.054	1910.0	1698.3	211.7	64,788	13,715,620	-734,063
66	-0.001696	49	-0.001113	178.6	-0.199	1735.0	1687.3	47.7	30,975	1,477,508	-293,616
67	-0.001885	70	-0.000645	54.3	-0.035	1790.0	1635.3	154.7	46,543	7,200,202	-252,062
78	-0.002924	0	0.000000	36.2	0.000	1775.0	1608.3	166.7	9,834	1,639,328	0
49	-0.002924	0	0.000000	19.3	0.000	1765.0	1611.0	154.0	10,939	1,684,606	0
50	-0.002924	26	-0.002628	11.1	-0.029	1750.0	1605.0	145.0	18,572	2,692,940	-78,557
75	-0.002924	26	-0.002628	18.7	-0.049	1730.0	1598.7	131.3	14,537	1,908,708	-93,803
68	-0.002924	26	-0.002628	35.5	-0.093	1715.0	1593.3	121.7	37,939	4,617,176	-430,767
69	-0.002827	29	-0.002473	69.4	-0.172	1670.0	1596.3	73.7	33,140	2,442,418	-419,107
70	-0.002827	29	-0.002473	121.3	-0.300	1630.0	1544.3	85.7	37,584	3,220,949	-966,028
71	-0.002827	29	-0.002473	175.5	-0.434	1595.0	1505.0	90.0	36,660	3,299,400	-1,431,717
77	-0.002310	63	-0.001049	121.7	-0.128	1585.0	1468.7	116.3	51,693	6,011,896	-767,292
72	-0.002310	63	-0.001049	53.8	-0.056	1505.0	1430.3	74.7	40,925	3,057,098	-172,485
37	-0.002310	63	-0.001049	17.7	-0.019	1480.0	1417.5	62.5	3,374	210,875	-3,914
74	-0.001571	51	-0.000989	21.5	-0.021	1475.0	1409.0	66.0	31,526	2,080,716	-44,228
73	-0.001571	51	-0.000989	18.9	-0.019	1445.0	1365.7	79.3	27,643	2,192,090	-40,961

Total Estimated 1950 Boundary Flow = -5,728,601

Ground Water Model
Fixed Flow Boundary Estimates
Eastern Boundary
1950 G.W. Level - Layer 5
Updated 07/18/05

Boundary Arc No.	Gradient Crossing Boundary (ft./ft.)	Gradient Angle At Boundary (deg)	Gradient Perpendicular To Boundary (ft./ft.)	Weighted Hyd. Cond. At Boundary (ft./d)	Weighted G.W. Velocity At Boundary (ft./d)	1950 Groundwater Elevation (ft.>msl)	Bottom Layer 5 Elevation (ft.>msl)	Saturated Thickness At Boundary (ft.)	Boundary Arc Length (ft.)	Boundary Flow Area (ft.2)	Boundary Flow (ft.3/d)
27	-0.001333	34	-0.001105	13.3	-0.015	1440.0	1323.2	116.8	11,533	1,347,054	-19,799
1	-0.001097	59	-0.000565	23.8	-0.013	1443.0	1318.4	124.6	9,800	1,220,753	-16,415
5	-0.001296	81	-0.000203	22.8	-0.005	1455.0	1304.0	151.0	15,820	2,388,820	-11,042
2	-0.001296	81	-0.000203	14.0	-0.003	1480.0	1298.4	181.6	23,550	4,276,680	-12,139
3	-0.002455	41	-0.001853	12.8	-0.024	1487.0	1302.1	184.9	26,940	4,981,206	-118,134
4	0.002261	0	0.000000	20.7	0.000	1555.0	1260.0	295.0	51,610	15,224,950	0
6	-0.002665	75	-0.000690	21.4	-0.015	1570.0	1207.1	362.9	33,086	12,006,909	-177,230
19	-0.001964	50	-0.001262	31.6	-0.040	1505.0	1206.0	299.0	26,280	7,857,720	-313,468
18	-0.001399	29	-0.001224	35.8	-0.044	1485.0	1210.9	274.1	34,070	9,338,587	-409,073
17	-0.001399	29	-0.001224	52.3	-0.064	1473.0	1191.8	281.2	8,860	2,491,432	-159,436
25	-0.001399	29	-0.001224	32.8	-0.040	1465.0	1267.9	197.1	24,300	4,789,530	-192,222
16	-0.001565	74	-0.000431	24.3	-0.010	1472.0	1318.6	153.4	18,560	2,847,104	-29,844
15	-0.001565	74	-0.000431	62.0	-0.027	1500.0	1318.3	181.7	19,950	3,624,915	-96,949
14	-0.001565	74	-0.000431	124.9	-0.054	1520.0	1310.1	209.9	13,430	2,818,957	-151,881
13	-0.001565	74	-0.000431	131.8	-0.057	1540.0	1308.8	231.2	12,850	2,970,920	-168,911
12	-0.001565	74	-0.000431	138.2	-0.060	1552.0	1328.8	223.2	10,080	2,249,856	-134,127
11	-0.001565	74	-0.000431	100.4	-0.043	1570.0	1371.8	198.2	13,820	2,739,124	-118,631
10	-0.001565	74	-0.000431	52.5	-0.023	1590.0	1409.6	180.4	8,470	1,527,988	-34,604
9	-0.001565	90	0.000000	45.2	0.000	1600.0	1425.0	175.0	5,450	953,750	0
8	-0.001565	90	0.000000	35.1	0.000	1615.0	1449.2	165.8	12,070	2,001,206	0
7	-0.001565	90	0.000000	22.4	0.000	1630.0	1489.1	140.9	9,460	1,332,914	0
26	-0.001399	90	-0.001399	23.4	-0.033	1638.0	1512.3	125.7	18,456	2,319,919	-75,946
20	-0.001399	90	-0.001399	72.3	-0.101	1640.0	1471.9	168.1	28,943	4,865,318	-492,116
21	-0.001399	90	-0.001399	30.0	-0.042	1647.0	1506.0	141	30,370	4,282,170	-179,723
22	-0.001794	41	-0.001354	77.2	-0.105	1595.0	1388.6	206.4	52,830	10,904,112	-1,139,751
23	-0.001696	22	-0.001573	117.6	-0.185	1577.0	1314.5	262.5	14,429	3,787,613	-700,430
24	-0.001555	7	-0.001543	109.1	-0.168	1575.0	1364.0	211	35,841	7,562,451	-1,273,411

Total Estimated 1950 Boundary Flow = -6,025,283

Ground Water Model
Fixed Flow Boundary Estimates
Western Boundary
1950 G.W. Level - Layer 5
Updated 07/18/05

Boundary Arc No.	Gradient Crossing Boundary (ft./ft.)	Gradient Angle At Boundary (deg)	Gradient Perpendicular To Boundary (ft./ft.)	Weighted Hyd. Cond. At Boundary (ft./d)	Weighted G.W. Velocity At Boundary (ft./d)	1950 Groundwater Elevation (ft.>msl)	Bottom Layer 5 Elevation (ft.>msl)	Saturated Thickness At Boundary (ft.)	Boundary Arc Length (ft.)	Boundary Flow Area (ft.2)	Boundary Flow (ft.3/d)
1	0.000891	0	0.000891	29.5	0.026	1902.0	1745.3	156.7	10,227	1,602,571	42,123
2	0.001382	45	0.000977	56.5	0.055	1903.0	1782.5	120.5	12,141	1,462,991	80,776
4	0.003388	26.5	0.003032	50.5	0.153	1920.0	1812.4	107.6	9,090	978,084	149,762
12	0.002875	18.4	0.002728	45.0	0.123	1932.0	1811.7	120.3	12,930	1,555,479	190,952
3	0.002964	26.5	0.002653	48.5	0.129	1930.0	1784.8	145.2	13,060	1,896,312	243,961
13	0.002341	34.5	0.001929	54.1	0.104	1955.0	1720.3	234.7	26,130	6,132,711	640,096
5	0.002145	19.3	0.002024	51.6	0.104	1985.0	1694.7	290.3	25,910	7,521,673	785,727
6	0.001969	17.6	0.001877	50.0	0.094	2008.0	1768.2	239.8	40,530	9,719,094	912,056
7	0.001607	45	0.001136	40.7	0.046	2003.0	1818.3	184.7	35,491	6,555,188	303,166
14	0.001786	45	0.001263	31.9	0.040	1982.0	1797.9	184.1	11,750	2,163,175	87,146
8	0.001684	0	0.001684	17.6	0.030	1972.0	1759.4	212.6	34,700	7,377,220	218,649
9	0.001684	0	0.001684	10.0	0.017	1978.0	1731.2	246.8	14,990	3,699,532	62,300
10	0.001752	27.6	0.001553	9.2	0.014	1978.0	1722.8	255.2	10,340	2,638,768	37,693
11	0.001906	56.9	0.001041	19.2	0.020	1960.0	1713.6	246.4	19,299	4,755,274	95,033

Total Estimated 1950 Boundary Flow = 3,849,440

APPENDIX B

RIVER BED CONDUCTANCE

PLATTE RIVER

Platte River
Average Bed Conductance
Between Hwy. 34 And Chapman Bridges
Based On Permeameter Tests and Geoprobe Borings
UNL Conservation and Survey - August 2005

Transect	Site	K_{v1} (ft/d)	K_{v2} (ft/d)	Ecbase (mS/m)	M_1 (ft)	M_2 (ft)	K_v (ft/d)	L (ft)	W (ft)	M (ft)	C (ft^2/d/ft)
A1	NC	78.7	0.056	35	13.8	6.8	0.169	1	1	20.6	0.0082
A2	MC	78.7	0.056	35	15.9	6.9	0.185	1	1	22.8	0.0081
A3	SC	78.7	0.056	35	12.4	13.3	0.108	1	1	25.7	0.0042
B1	NC	109.7	0.056	35	21.6	1.7	0.763	1	1	23.3	0.0327
B2	MC	109.7	0.056	35	10.8	9.5	0.120	1	1	20.3	0.0059
B3	SC	109.7	0.056	35	8.5	8.1	0.115	1	1	16.6	0.0069

Average Unit C = 0.0110 ft^2/d per foot of river reach per foot of river width
Total Conductance C 11.0 ft^2/d per foot of river reach (using a river bed with of 1,000 ft.)

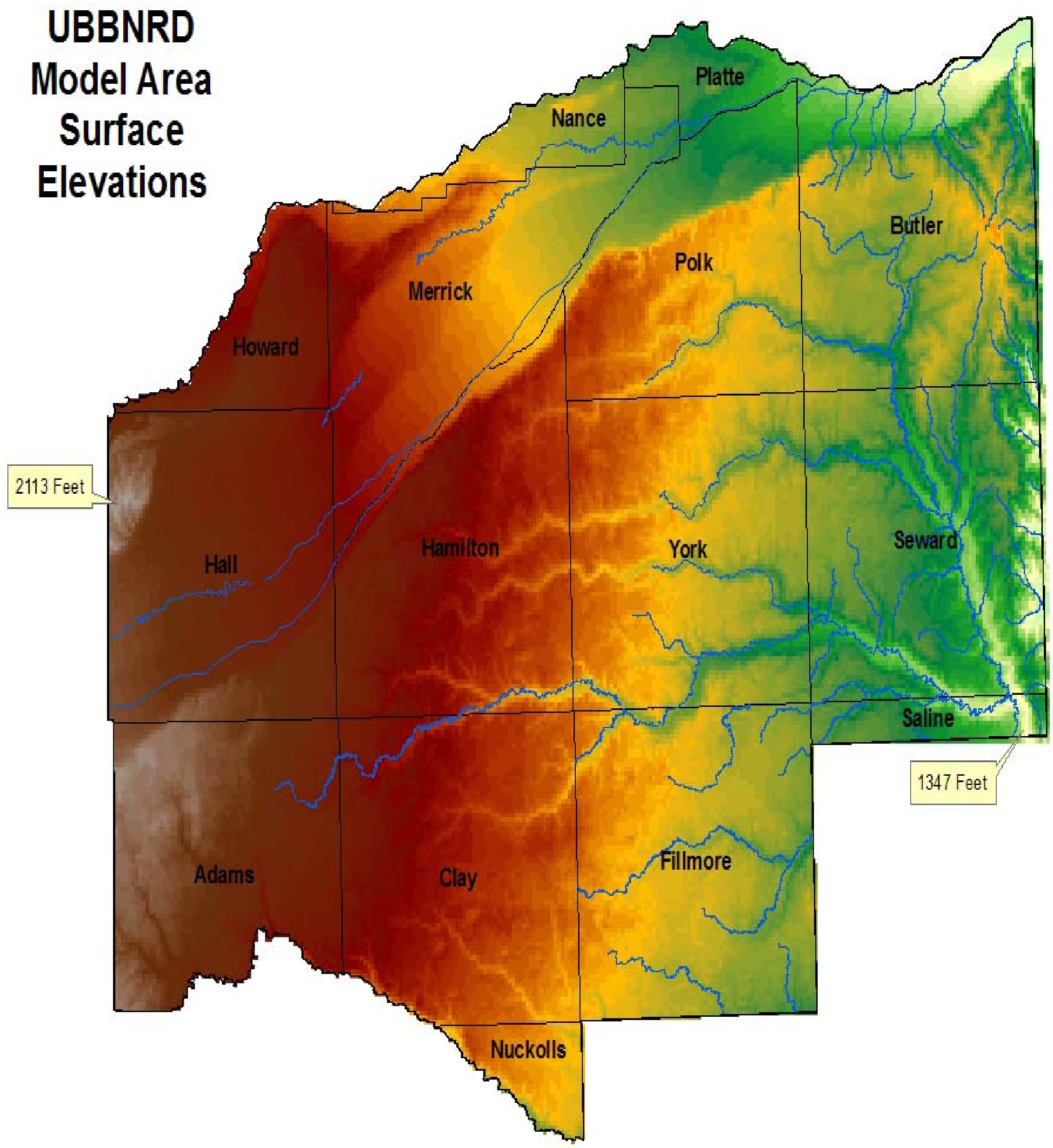
NOTES:
1. NC = North Channel
2. MC = Middle Channel
3. SC = South Channel
4. Site A is located in Sec 29, Twp 11N, Rng 8W, and is upstream from the BNSF railroad bridge over the Platte River near Grand Island
5. Site B is located in the NW^4 Sec 11, Twp 11N, Rng 8W, and is near the upstream from the Chapman Bridge near the intersection of 5^{th} and B Streets
6. K_{v1} = vertical hydraulic conductivity of river bed material with EC log < 35 mS/m
7. K_{v2} = vertical hydraulic conductivity of river bed material with EC log >= 35 mS/m
8. K_v = wighted vertical hydraulic conductivity for total river bed thickness M
9. L = river reach length (use 1.0 ft. for this calculation)
10. W = river bed width (use 1.0 ft. to compute the unit condutance.
Apply total river bed width of 1,000 ft. to determine total bed conductance per linear foot of river reach between Hwy. 34 bridge and Chapman bridge
11. M1 = thickness of the river bed material with EC log < 35 mS/m)
(based on CSD geoprobe resistivity log)
12. M2 = thickness of the river bed material with EC log >= 35 mS/m)
(based on CSD geoprobe resistivity log)
13. M = total river bed thickness ($M_1 + M_2$)
14. Equation for computing river bed conductance

$$C = \frac{K_v \times L \times W}{M}$$

15. Equation for weighting vertical hydraulic conductivity:

$$Kv = \frac{M}{(M_1/K_{v1}) + (M_2/K_{v2})}$$

APPENDIX C
GROUNDWATER LEVEL MAPS
DEPTH TO GROUNDWATER


UBBNRD
Model Area
Surface
Elevations
Platte
Nance
Butler
Polk
Merrick
Howard
2113 Feet
Hamilton
York
Seward
Hall
Saline
1347 Feet
Adams
Clay
Fillmore
Nuckolls

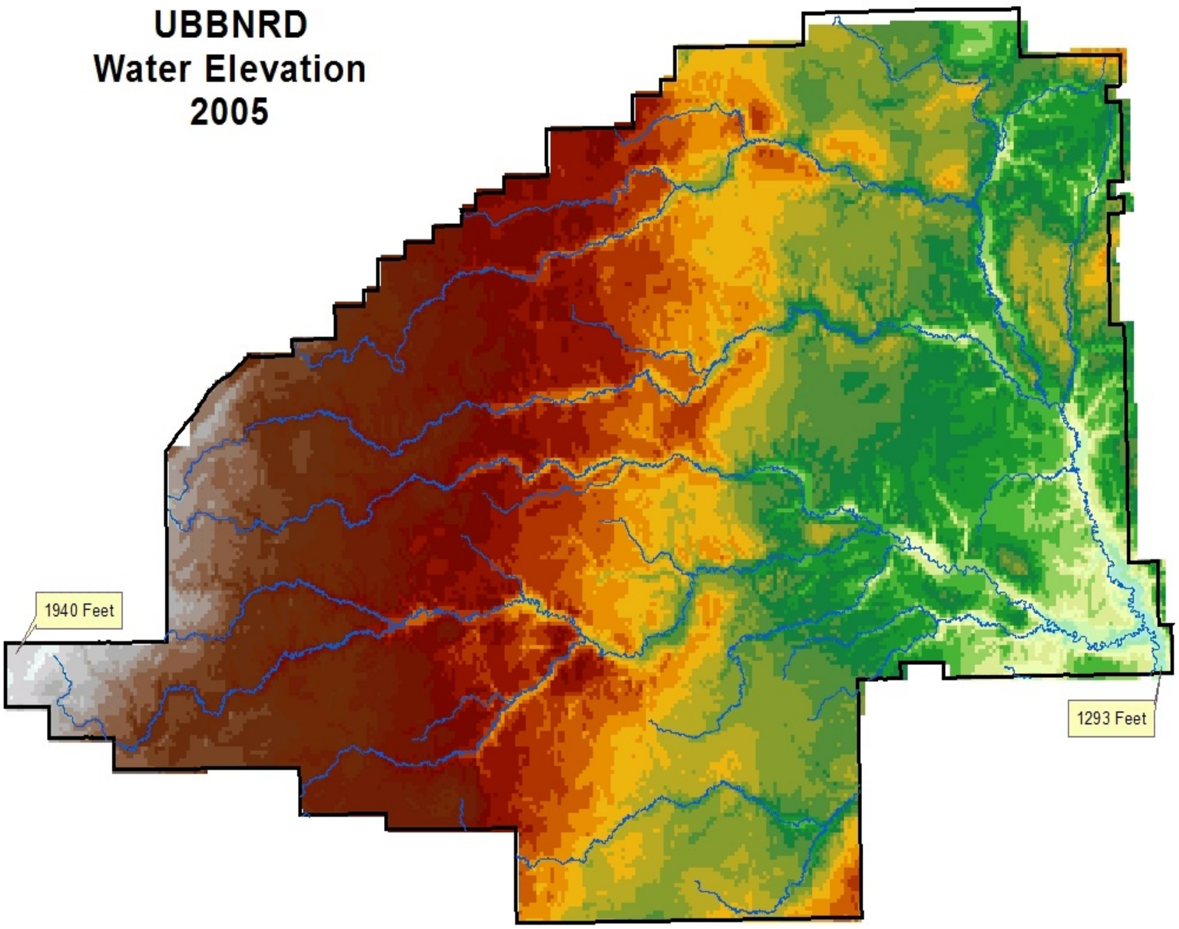


FIGURE 7

GENERAL GROUNDWATER ELEVATION MODEL

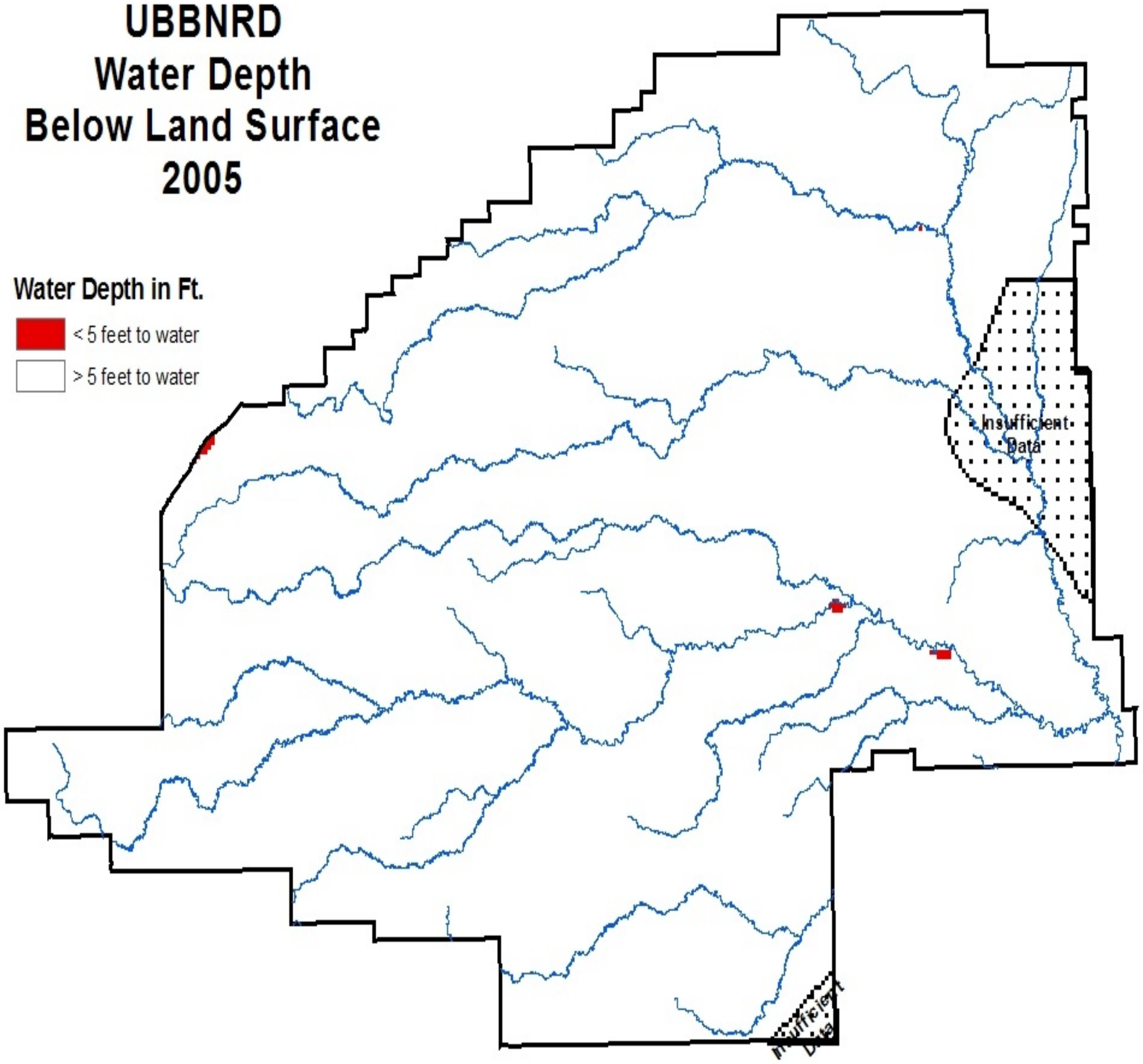


FIGURE 8

GENERAL DEPTH OF GROUNDWATER BELOW LAND SURFACE

Appendix F

Techniques of Water-Resources Investigations of the United States Geological Survey

Chapter D1

COMPUTATION OF RATE AND VOLUME OF STREAM DEPLETION BY WELLS

By C. T. Jenkins

Book 4

HYDROLOGIC ANALYSIS AND INTERPRETATION

UNITED STATES DEPARTMENT OF THE INTERIOR

CECIL D. ANDRUS, Secretary

GEOLOGICAL SURVEY

V. E. McKelvey, Director

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PREFACE

The series of manuals on techniques describes procedures for planning and executing specialized work in water-resources investigations. The material is grouped under major subject headings called books and further subdivided into sections and chapters; Section D of Book 4 is on interrelated phases of the hydrologic cycle.

The unit of publication, the chapter, is limited to a narrow-field of subject matter. This format permits flexibility in revision and publication as the need arises.

Provisional drafts of chapters are distributed to field offices of the U.S. Geological Survey for their use. These drafts are subject to revision because of experience in use or because of advancement in knowledge, techniques, or equipment. After the technique described in a chapter is sufficiently developed, the chapter is published and is sold by the U.S. Geological Survey, 1200 South Eads Street, Arlington, VA 22202 (authorized agent of Superintendent of Documents, Government Printing Office).

This manual is an expanded version of a paper, "Techniques for computing rate and volume of stream depletion of wells" (Jenkins, 1968a), that was prepared in the Colorado District, Water Resources Division, in cooperation with the Colorado Water Conservation Board and the Southeastern Colorado Water Conservancy District and published in Ground Water, the journal of the Technical Division, National Water Well Association.

CONTENTS

	Page
Preface	III
Abstract	1
Introduction	1
Definitions and assumptions	2
Descriptions of curves and tables	3
Effects during pumping	3
Residual effects	4
Intermittent pumping	5
Sample computations	8
Mathematical bases for curves and tables	16
Definitions	16
Mathematical base for curve *A*	16
Mathematical base for curve *B*	16
References	17

FIGURES

	Page
1. Curves to determine rate and volume of stream depletion	4
2. Curves to determine rate of stream depletion during and after pumping	6
3. Curves to determine volume of stream depletion during and after pumping	7
4. Example of residual effects of well pumping 35 days	7
5. Curves showing the effects of intermittent and steady pumping on a stream	10

TABLES

	Page
1. Values of q/Q, $\frac{v}{Qt}$, and $\frac{v}{Qsdf}$ corresponding to selected values of t/sdf	5
2. Computation of residual effects of pumping	6
3. Computation of the effects of two selected patterns of pumping on a nearby stream	8

COMPUTATION OF RATE AND VOLUME OF STREAM DEPLETION BY WELLS

By C. T. Jenkins

Abstract

When field conditions approach certain assumed conditions, the depletion in flow of a nearby stream caused by pumping a well can be calculated readily by using dimensionless curves and tables. Computations can be made of (1) the rate of stream depletion at any time during the pumping period or the following nonpumping period, (2) the volume of water induced from the stream during any period, pumping or nonpumping, and (3) the effects, both in rate and volume of stream depletion, of any selected pattern of intermittent pumping. Sample computations illustrate the use of the curves and tables. An example shows that intermittent pumping may have a pattern of stream depletion not greatly different from a pattern for steady pumping of an equal volume.

The residual effects of pumping, that is, effects after pumping stops, on streamflow may often be greater than the effects during the pumping period. Adequate advance planning that includes consideration of residual effects thus is essential to effective management of a stream-aquifer system.

Introduction

With increasing frequency, problems of water management require evaluation of effects of ground-water withdrawal on surface supplies. Both rate and volume effects have significance. Effects after the pumping stops (called residual effects in this paper) are important also but have not previously been examined in detail. In fact, residual effects can be much greater than those during pumping. Curves and tables shown in this paper, although applicable to a large range of interactions, are especially oriented to the solution of problems involving very small interactions and to the evaluation of residual effects. Where many wells are concentrated near a stream, the combined withdrawals can have a significant effect on the availability of water in the stream.

In some instances, especially in the evaluation of residual effects, the grid spacing on the charts shown may prove to be too coarse to provide the desired precision. However, this precision can be attained either by interpolating between the tabular values supplied or by using curves prepared by plotting the tabular values on commercially available chart paper that is more finely divided.

The relations between the pumping of a well and the resulting depletion of a nearby stream have been derived by several investigators (Theis, 1941; Conover, 1954; Glover and Balmer, 1954; Glover, 1960; Theis and Conover, 1963; Hantush, 1964, 1965). The relations generally are shown in the form of equations and charts; however, except for the charts shown by Glover (1960), which were in a publication that had limited distribution, the charts are useful as computational tools only in the range of comparatively large effects, and rather formidable equations must be solved to evaluate small effects. The average user retreats in dismay when faced by the mysticism of "line source integral," "complementary error function," or "the second repeated integral of the error function." The primary purpose of this report is to provide tools that will simplify the seemingly intricate computations and to give examples of their use.

Because this writer definitely is a member of the community of "average users," he has exercised what he believes to be his prerogative of reversing the usual order of presentation. In this paper, the working tools—curves, tables, and sample computations—are shown first, and the discussion of their mathematical bases is relegated to the end of the report. The usefulness of the tools will not be greatly enhanced by an understanding of the material at the end of the report; it is shown for the benefit of those who desire to examine the mathematical bases of the tools.

The techniques demonstrated in this paper are not new, but they seem to have been rather well concealed from most users in the past. Their value to water managers is apparent, especially in the estimation of total volume of depletion and of residual effects.

Virtually all the literature that discusses the effects of pumping on streamflow fails to mention that the effects of recharge are identical, except for direction of flow. (See Glover, 1964, p. 48.) Only pumping will be considered in this paper, but the reader should be aware that the terms "recharging" and "accretion" can be substituted for "pumping" and "depletion," respectively.

Definitions and Assumptions

To avoid confusion owing to the use of the same symbol for the dimension time as for transmissivity, symbols for the dimensions time and length are set in Roman type, are capitalized, and are enclosed in brackets. All other symbols, except that designating the mathematical term "second repeated integral," are set in italics.

Stream depletion means either direct depletion of the stream or reduction of ground-water flow to the stream.

The symbols used in the main body of the report are defined below (those that have to do only with the mathematical bases are defined at the end of the report in the section on this subject):

T= transmissivity, $[\mathrm{L}^2/\mathrm{T}]$;
S= the specific yield of the aquifer, dimensionless;
t= time, during the pumping period, since pumping began, $[\mathrm{T}]$;
t_p= total time of pumping, $[\mathrm{T}]$;
t_i= time after pumping stops, $[\mathrm{T}]$;
Q= the net steady pumping rate, $[\mathrm{L}^3/\mathrm{T}]$; the steady pumping rate less the rate at which pumped water returns to the aquifer;
q= the rate of depletion of the stream, $[\mathrm{L}^3/\mathrm{T}]$;
Qt= the net volume pumped during time t, $[\mathrm{L}^3]$;
Qt_p= the net volume pumped, $[\mathrm{L}^3]$;
v= the volume of stream depletion during time t, t_p, or t_p+t_i, $[\mathrm{L}^3]$;
a= the perpendicular distance from the pumped well to the stream, $[\mathrm{L}]$;
sdf= the stream depletion factor, $[\mathrm{T}]$.

The term "stream depletion factor" was introduced by Jenkins (1968a). It is arbitrarily defined as the time coordinate of the point where v=28 percent of Qt on a curve relating v and t. If the system meets the assumptions listed in this section, $sdf=a^2S/T$; in a complex system it can be considered to be an effective value of a^2S/T. The value of the sdf at any location in the system depends upon the integrated effects of the following: Irregular impermeable boundaries, stream meanders, aquifer properties and their areal variation, distance from the stream, and imperfect hydraulic connection between the stream and the aquifer.

The curves and tables in this report are dimensionless and can be used with any units. The units in the system must be consistent, however. For example, if Q and q are in acre-feet per day (acre-ft/day), v must be in acre-feet (acre-ft). If a is in feet (ft) and T/S is in gallons per day per foot (gal/day-ft), the value of T/S must be converted to square feet per day (ft^2/day). A T/S value of 10^6gal/day-ft equals $(10^6\text{gal/day-ft})\times(1\text{ft}^3/7.48\text{ gal})$ equals 134,000 ft^2/day.

The assumptions made for this analysis are the same as other investigators have made and are as follows:

1. T does not change with time. Thus for a water-table aquifer, drawdown is considered to be negligible when compared to the saturated thickness.
2. The temperature of the stream is assumed to be constant and to be the same as the temperature of the water in the aquifer.
3. The aquifer is isotropic, homogeneous, and semi-infinite in areal extent.
4. The stream that forms a boundary is straight and fully penetrates the aquifer.
5. Water is released instantaneously from storage.
6. The well is open to the full saturated thickness of the aquifer.
7. The pumping rate is steady during any period of pumping.

Field conditions never meet fully the idealized conditions described by the above assumptions.

The usefulness of the tools presented in this report will depend to a large extent on the degree to which the user recognizes departures from ideal conditions, and on how well he understands the effects of these departures on stream depletion.

Departure from idealized conditions may cause actual stream depletions to be either greater or less than the values determined by methods presented in this report. Although the user usually cannot determine the magnitude of these discrepancies, he should, where possible, be aware of the direction the discrepancies take.

Jenkins (1968b) has described the use of a model to evalute the effects on stream depletion of certain departures from the ideal. If a model is not available, the user of this report can be guided in estimating the *sdf* by the effects calculated in that report for selected departures from the idealized system. Intuitive reasoning will be useful in estimating the effects of departures from the ideal that are difficult to incorporate in a model. For example, where drawdowns at the well site are a substantial proportion of the aquifer thickness, T will decrease significantly. A decrease in T results in a decrease in the amount of stream depletion relative to the amount of water pumped.

Variations in water temperatures will cause variations in stream depletion, especially by large-capacity wells near the stream. Warm water is less viscous than cold water; hence stream depletion will be somewhat greater in the summer than in the winter, given the same pattern of pumping. Stream stages affect water-table gradients, and hence stream depletion.

Lowering of the water table on a flood plain may result in the capture of substantial amounts of water that would otherwise be transpired. The effect is similar to intercepting another recharge boundary, and the proportion of stream depletion to pumpage is decreased. Interception of a valley wall or other negative boundary will have the opposite effect.

If large-capacity wells are placed close to a stream, and streambed permeability is low compared to aquifer permeability, the water table may be drawn down below the bottom of the streambed. (See Moore and Jenkins, 1966.) Under these conditions, stream depletion depends upon streambed permeability, area of the streambed, temperature of the water, and stage of the stream, and the methods presented in this report are not applicable.

Both during and after pumping, some part and at times all of stream depletion can consist of ground water intercepted before reaching the stream. Thus a stream can be depleted over a certain reach, yet still be a gaining stream over that reach. The flow at the lower end of the reach is less than it would have been had depletion not occurred, and less by the amount of depletion. In order to predict the amount of streamflow at the lower end of the reach, residual effects of previous pumping or recharge must be considered. They can be approximately accounted for by using past records of pumping and recharge to "prestress" the calculations. The depletion due to the pumping under consideration will then be superimposed on the residual depletion, and the resultant value will be the net direct depletion from the stream.

Description of Curves and Tables

Effects during pumping

Curves A and B in figure 1 apply during the period of steady pumping. Curve A shows the relation between the dimensionless term t/sdf and the rate of stream depletion, q, at time t, expressed as a ratio to the pumping rate Q. Curve B shows the relation between t/sdf and the volume of stream depletion, v, during time t, expressed as a ratio to the volume pumped, Qt. The two curves labeled $1-q/Q$ and $1-\frac{v}{Qt}$ are shown to facilitate determination of values of q/Q and $\frac{v}{Qt}$ when the ratios exceed 0.5. The coordinates of curves A and B are tabulated in table 1. The number of significant figures shown for the values in table 1 was determined by needs for some of the computations described in the next section. Precision to more than two significant figures in reporting results probably will never be warranted.

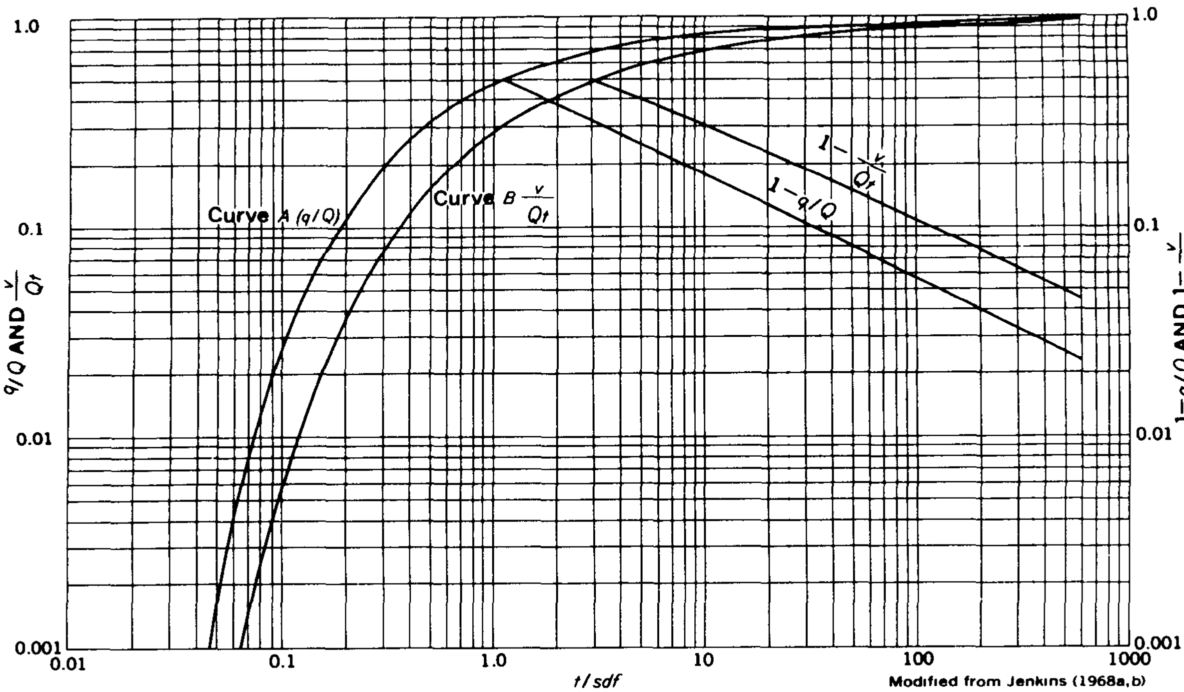

Figure 1.—Curves to determine rate and volume of stream depletion.

Residual effects

Stream depletion continues after pumping stops. As time approaches infinity, the volume of stream depletion approaches the volume pumped, if the assumption is made that the stream is the sole source of recharge. In any real case this is not true in the long term because precipitation and return flow from irrigation may represent the major portion of the recharge. To simplify the relation between well pumpage and stream depletion all other sources of water input are ignored in the following discussions. The rate and volume of depletion at any time after pumping ends can be computed by using the method of superposition, that is, by assuming that the pumping well continues to pump, and that an imaginary well at the same location is recharged continuously at the same rate the pumping well is discharging. The rate and volume of stream depletion at any time after pumping ends is equal to the differences between the rate and volume of depletion that would have occurred if pumping had continued, and the rate and volume of accretion resulting from recharge by the imaginary recharge well, starting from the time pumping ends.

Residual effects are shown in figures 2 and 3 for eight values of t_p/sdf. Problems concerned with values of t_p/sdf other than those for which curves are shown in figures 2 and 3 can be solved with an acceptable degree of accuracy by interpolation, but if the user desires a more accurate appraisal, separate computations can be made.

The computations shown in table 2, which are the basis for the curves labeled $t_p/sdf=0.35$ in figures 2 and 3 and for the curve in figure 4, will serve as an illustration of how additional curves can be constructed. As an aid to construction of curves such as those in figure 3, note that the curves are asymptotic to the ordinate $\frac{v}{Qsdf}$ $(=t_p/sdf)$.

Because Q is the same for both the pumping and recharging wells, residual q/Q can be computed directly from q/Q values in table 1. However, Qt is different for the two wells; so the ratios $\frac{v}{Qt}$ must be given a common denominator by multiplying by their respective values

Table 1.—Values of q/Q, $\frac{v}{Qt}$, and $\frac{v}{Qsdf}$ corresponding to selected values of t/sdf

$\frac{t}{sdf}$	q/Q	$\frac{v}{Qt}$	$\frac{v}{Qsdf}$
0	0	0	0
.07	.008	.001	.0001
.10	.025	.006	.0006
.15	.068	.019	.003
.20	.114	.037	.007
.25	.157	.057	.014
.30	.197	.077	.023
.35	.232	.097	.034
.40	.264	.115	.046
.45	.292	.134	.060
.50	.317	.151	.076
.55	.340	.167	.092
.60	.361	.182	.109
.65	.380	.197	.128
.70	.398	.211	.148
.75	.414	.224	.168
.80	.429	.236	.189
.85	.443	.248	.211
.90	.456	.259	.233
.95	.468	.270	.256
1.0	.480	.280	.280
1.1	.500	.299	.329
1.2	.519	.316	.379
1.3	.535	.333	.433
1.4	.550	.348	.487
1.5	.564	.362	.543
1.6	.576	.375	.600
1.7	.588	.387	.658
1.8	.598	.398	.716
1.9	.608	.409	.777
2.0	.617	.419	.838
2.2	.634	.438	.964
2.4	.648	.455	1.09
2.6	.661	.470	1.22
2.8	.673	.484	1.36
3.0	.683	.497	1.49
3.5	.705	.525	1.84
4.0	.724	.549	2.20
4.5	.739	.569	2.56
5.0	.752	.587	2.94
5.5	.763	.603	3.32
6.0	.773	.616	3.70
7	.789	.640	4.48
8	.803	.659	5.27
9	.814	.676	6.08
10	.823	.690	6.90
15	.855	.740	11.1
20	.874	.772	15.4
30	.897	.810	24.3
50	.920	.850	42.5
100	.944	.892	89.2
600	.977	.955	573

of t/sdf, to obtain the values given in table 1 for $\frac{v}{Qsdf}$. The "stepping" of the last six items in column 8, table 2, is the result of using linear interpolation in table 1. The errors are small and can be practically eliminated by drawing mean curves.

The magnitude, distribution, and extent of residual effects in a hypothetical field situation are shown in figure 4. The curve labeled q shows the relation between the rate of stream depletion, q, and time, t, resulting from pumping a well 3,660 feet from a stream at a rate of 10 acre-ft/day for 35 days. The ratio T/S is 134,000 ft ^{2}/day, which is not an unusual value for an alluvial aquifer. The *sdf* is 100 days. The pumping rate is 10 acre-ft/day; the maximum rate of stream depletion is 2.7 acre-ft/day. Pumping stops at the end of 35 days; the maximum rate of stream depletion occurs about 10 days later, and q still is about half the maximum rate 45 days after pumping stops.

The area in the rectangle under the line labeled Q represents total volume pumped; the area under the curve labeled q represents the volume of stream depletion. In terms of volume removed from the stream during the pumping period, the effect is small, only about 10 percent of the volume pumped. However, the effect continues, and as time approaches infinity, the volume of stream depletion approaches the volume pumped.

Consideration of such residual effects as are illustrated in figure 4 leads to the conclusion that the management of a system that uses both surface water and a connected ground-water reservoir requires a great deal of foresight. The immediate effects on streamflow of a change in pumping pattern may be very small; plans adequate for effective management of the resource generally require consideration of needs in the future—sometimes the distant future. The sample problems solved later in this report illustrate the value of long-range plans in water management.

Intermittent pumping

The curves in figure 5 illustrate the effect of one pattern of intermittent pumping. The computations are shown in table 3. Effects on the stream, both in volume removed and rate of removal are compared for two patterns of pumping of 63 acre-ft during a 42-day period. In both cases the aquifer has a ratio T/S of 134,000 ft^2/day, and the well is 1,890 feet from the stream; thus the value for the $sdf=$ 26.7 days. During steady pumping, the well is pumped at a rate of 1.5 acre-ft/day for 42 days. In the intermittent pattern, the well is pumped at a rate of 5.25 acre-ft/day for

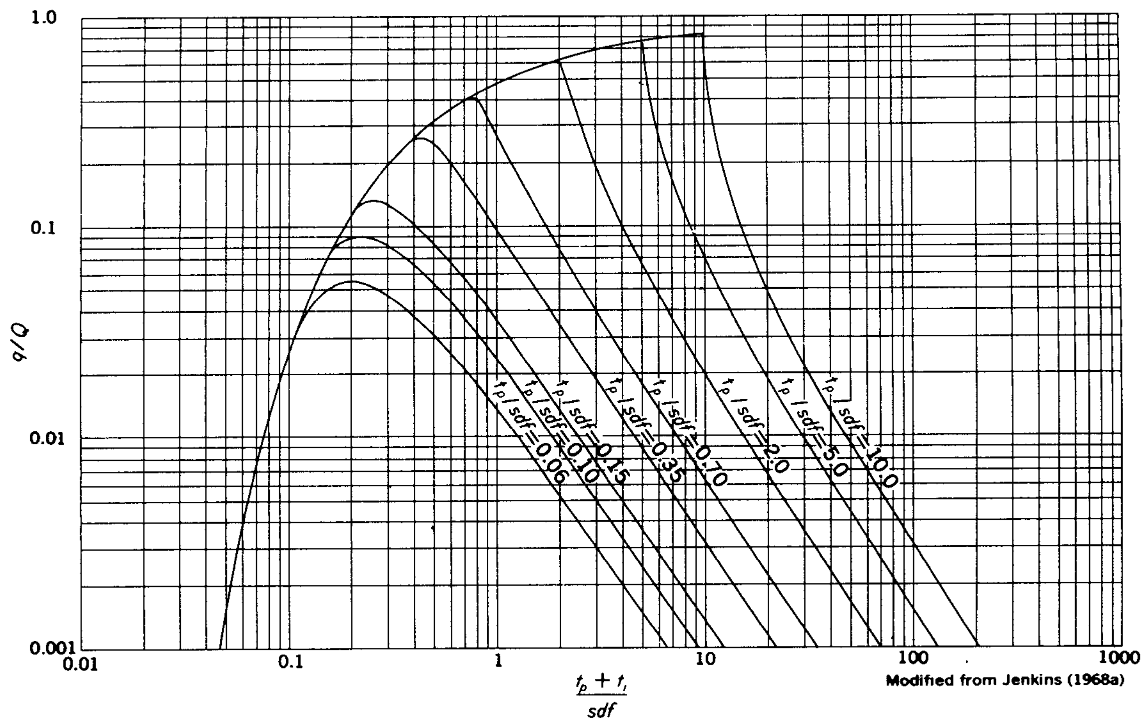

Figure 2.—Curves to determine rate of stream depletion during and after pumping.

Table 2.—Computation of residual effects of pumping

[Pumping stopped when t/sdf=0.35]

Pumped well			Recharged well			Residual	Residual
t/sdf	q/Q	$\frac{v}{Qsdf}$	t/sdf	q/Q	$\frac{v}{Qsdf}$	q/Q	$\frac{v}{Qsdf}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
0. 35	0. 232	0. 034	0	0	0	0. 232	0. 034
. 42	. 275	. 052	. 07	. 008	. 0001	. 267	. 052
. 45	. 292	. 060	. 10	. 025	. 0006	. 267	. 059
. 50	. 317	. 076	. 15	. 068	. 003	. 249	. 073
. 60	. 361	. 109	. 25	. 157	. 014	. 205	. 095
. 70	. 398	. 148	. 35	. 232	. 034	. 166	. 114
1. 00	. 480	. 280	. 65	. 380	. 128	. 099	. 152
1. 50	. 564	. 543	1. 15	. 510	. 354	. 053	. 189
2. 00	. 617	. 838	1. 65	. 581	. 629	. 035	. 209
3. 00	. 683	1. 49	2. 65	. 664	1. 255	. 019	. 235
5. 00	. 752	2. 94	4. 65	. 743	2. 67	. 009	. 27
7. 00	. 789	4. 48	6. 65	. 783	4. 21	. 006	. 27
10. 00	. 823	6. 90	9. 65	. 8198	6. 61	. 0032	. 29
15. 00	. 855	11. 1	14. 65	. 8528	10. 81	. 0022	. 29
20. 00	. 872	15. 3	19. 65	. 8718	15. 00	. 0012	. 30
30. 00	. 897	24. 3	29. 65	. 8961	23. 99	. 0009	. 31

1. $\frac{t_p+t_i}{sdf}=t/sdf$ for pumped well if pumping had continued.
2. q/Q for pumped well if pumping had continued. Values from table 1 for value of t/sdf indicated in column 1.
3. $\frac{v}{Qsdf}$ for pumped well if pumping had continued. Values from table 1 for value of t/sdf indicated in column 1.
4. t/sdf for recharged well, beginning at end of pumping.
5. q/Q for recharged well, beginning at end of pumping. Values from table 1 for value of t/sdf indicated in column 4.
6. $\frac{v}{Qsdf}$ for recharged well, beginning at end of pumping. Values from table 1 for value of t/sdf indicated in column 4.
7. Column 2 minus column 5; residual q/Q.
8. Column 3 minus column 6; residual $\frac{v}{Qsdf}$.

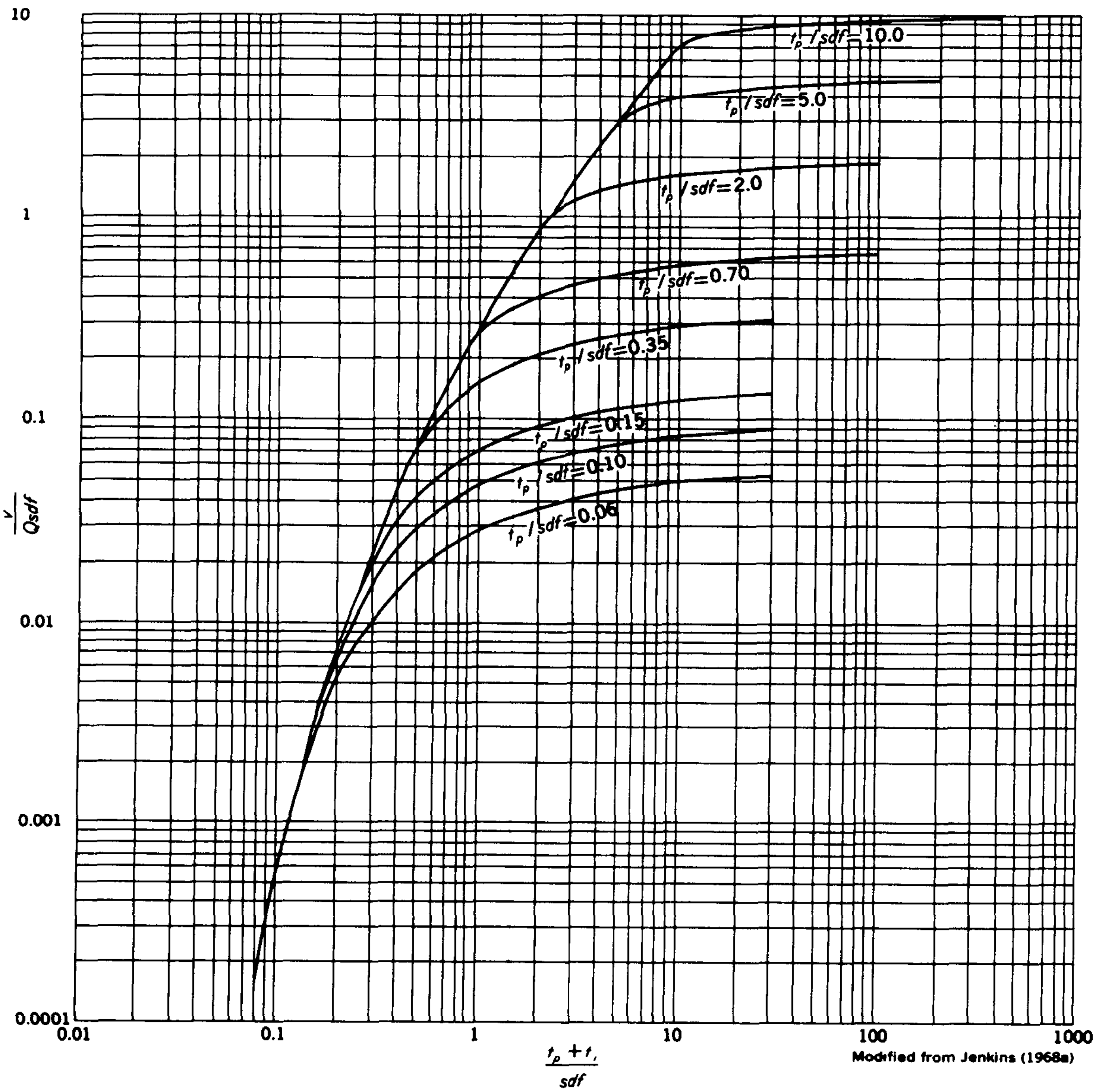

Figure 3.—Curves to determine volume of stream depletion during and after pumping.

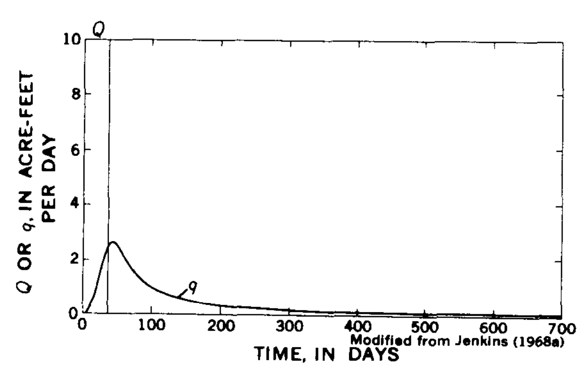

Figure 4.—Example of residual effects of well pumping 35 days.

4 days beginning 5 days after the beginning of the period, shut down 10 days, pumped 4 days, shut down 10 days, pumped 4 days, and shut down 5 days. The computed effects of the pattern of intermittent pumping are compared in figure 5 with those of the steady rate. The comparisons indicate that, within quite large ranges of intermittency, the effects of intermittent pumping are approximately the same as those of steady, continuous pumping of the same volume.

Table 3.—Computation of the effects of two selected

[a=1,890 ft, T/S=134,000 ft²/day, sdf=26.7 days. Intermittent pumping rate=5.25 acre-ft/day,

Time from beginning of period (days)	Steady pumping: Pumping period (1st–42d day inclusive)					Intermittent pumping: Pumping period (6th–9th day inclusive)			
	t/sdf	q/Q	$\frac{v}{Qsdf}$	q (acre-ft per day)	v (acre-ft)	Time (days)	t/sdf	q/Q	$\frac{v}{Qsdf}$
0	0	0	0	0	0				
5	.187	.102	.006	.15	.2	0	0	0	0
9	.337	.223	.031	.33	1.2	4	.150	.068	.003
12	.449	.291	.060	.44	2.4	7	.262	.127	.015
19	.712	.402	.153	.60	6.1	14	.524	.080	.044
23	.861	.446	.216	.67	8.7	18	.674	.061	.054
26	.974	.471	.262	.71	10.5	21	.787	.050	.061
33	1.236	.525	.398	.79	15.9	28	1.049	.034	.071
37	1.386	.548	.479	.82	19.2	32	1.199	.029	.074
42	1.573	.573	.585	.86	23.4	37	1.386	.023	.081

Sample Computations

To illustrate the use of the curves and tables, solutions are shown of problems that might arise in the conjunctive management of ground water and surface water.

Problem I

Management criteria require that pumping cease when the rate of stream depletion by pumping reaches 0.14 acre-ft/day:

1. Under this restriction how long can a well 1.58 miles from the stream be pumped at the rate of 2 acre-ft/day if T/S is 10^6 gal/day-ft, and what is the volume of stream depletion during this time?
2. If pumping this well is stopped when q=0.14 acre-ft/day, what will the rate of stream depletion be 30 days later? What will be the volume of stream depletion at that time?
3. What will be the largest rate of stream depletion and when will it occur?

Given:

q=0.14 acre-ft/day
Q=2 acre-ft/day
a=1.58 miles
$T/S=10^6$ gal/day-ft
t_i=30 days

$$sdf=a^2S/T=\frac{a^2}{T/S}=\frac{(1.58\text{ mi})^2\,(5{,}280\text{ ft/mi})^2}{(10^6\text{ gal/day-ft})\,(1\text{ ft}^3/7.48\text{ gal})}$$
$$=520\text{ days.}$$

Find:

t_p
v at t_p
q at t_p+t_i
v at t_p+t_i
q max
t of q max.

Part 1

From information given, the ratio of the rate of stream depletion to the rate of pumping is

$$q/Q=\frac{(0.14\text{ acre-ft/day})}{(2\text{ acre-ft/day})}=0.07.$$

From curve A (fig. 1)

$$t/sdf=0.15.$$

Substitute the value under "Given" for sdf, and

$$t=(0.15)(520\text{ days})=78\text{ days.}$$

The total time the well can be pumped is 78 days.

When

$$t/sdf=0.15.$$

then from curve B (fig. 1),

$$\frac{v}{Qt}=0.02.$$

Substitute the values for Q and t, and the volume of stream depletion during this time is

$$v=(0.02)(2\text{ acre-ft/day})(78\text{ days})$$
$$=3.1\text{ acre-ft.}$$

patterns of pumping on a nearby stream

$t_p/sdf=0.15$ (see curves in figures 2 and 3). Steady pumping rate=1.5 acre-ft/day]

Intermittent pumping—Continued											
Pumping period (20th–23d day inclusive)				Pumping period (32d–35th day inclusive)				Totals			
Time (days)	t/sdf	q/Q	$\frac{v}{Qsdf}$	Time (days)	t/sdf	q/Q	$\frac{v}{Qsdf}$	q/Q	$\frac{v}{Qsdf}$	q (acre-ft per day)	v (acre-ft)
								0	0	0	0
								.068	.003	.36	.4
								.127	.015	.67	2.1
0	0	0	0					.080	.044	.42	6.2
4	.150	.068	.003					.129	.057	.68	8.0
7	.262	.127	.015					.177	.076	.93	10.7
14	.524	.080	.044	0	0	0	0	.114	.115	.60	16.1
18	.674	.061	.054	4	.150	.068	.003	.158	.131	.83	18.4
23	.861	.044	.063	9	.337	.223	.031	.188	.169	.99	23.7

During the 78-day pumping period, 3.1 acre-ft, out of a total of 156 acre-ft pumped, is stream depletion.

Part 2

If pumping is stopped at the end of 78 days, then $t_p/sdf=0.15$, and 30 days later,

$$\frac{t_p+t_i}{sdf}=\frac{108 \text{ days}}{520 \text{ days}}=0.21.$$

From figure 2: if

$$t_p/sdf=0.15$$

and

$$\frac{t_p+t_i}{sdf}=0.21,$$

$$q/Q=0.12.$$

Thus the rate of stream depletion is

$$\begin{aligned} q &= (0.12)(2 \text{ acre-ft/day}) \\ &= 0.24 \text{ acre-ft/day, 30 days after pumping stops.} \end{aligned}$$

From figure 3

$$\frac{v}{Qsdf}=0.008.$$

Substitute the values for Q and sdf, and the total volume of the stream depletion at the end of 30 days is

$$\begin{aligned} v &= (0.008)(2 \text{ acre-ft/day})(520 \text{ days}) \\ &= 8.3 \text{ acre-ft of stream depletion during 108 days} \end{aligned}$$

as a result of pumping 2 acre-ft/day during the first 78 days.

Part 3

If

$$t_p/sdf=0.15,$$

then from figure 2

$$\text{maximum } q/Q=0.13,$$

when

$$\frac{t_p+t_i}{sdf}=0.25.$$

Therefore

$$\begin{aligned} \text{maximum } q &= (0.13)(2 \text{ acre-ft/day}) \\ &= 0.26 \text{ acre-ft/day} \end{aligned}$$

when

$$\begin{aligned} t_p+t_i &= (0.25)(520 \text{ days}) \\ &= 130 \text{ days, or 52 days after pumping stops.} \end{aligned}$$

Problem II

An irrigator is restricted to a maximum withdrawal of 150 acre-ft during the 150-day growing season, provided his pumping depletes the stream less than 25 acre-ft during the season. His well is 1 mile from the stream, and $T/S=134{,}000$ ft²/day. He will pump at the rate of 2.00 acre-ft/day, regulating his average pumping rate by shutting his pump off for the appropriate number of hours per day. Examine the effects of several possible pumping patterns: Given:

$\max = Qt$ 150 acre-ft
$v \max = 25$ acre-ft
$t \max = 150$ days
$a = 1$ mile
$T/S = 134{,}000$ ft^2/day

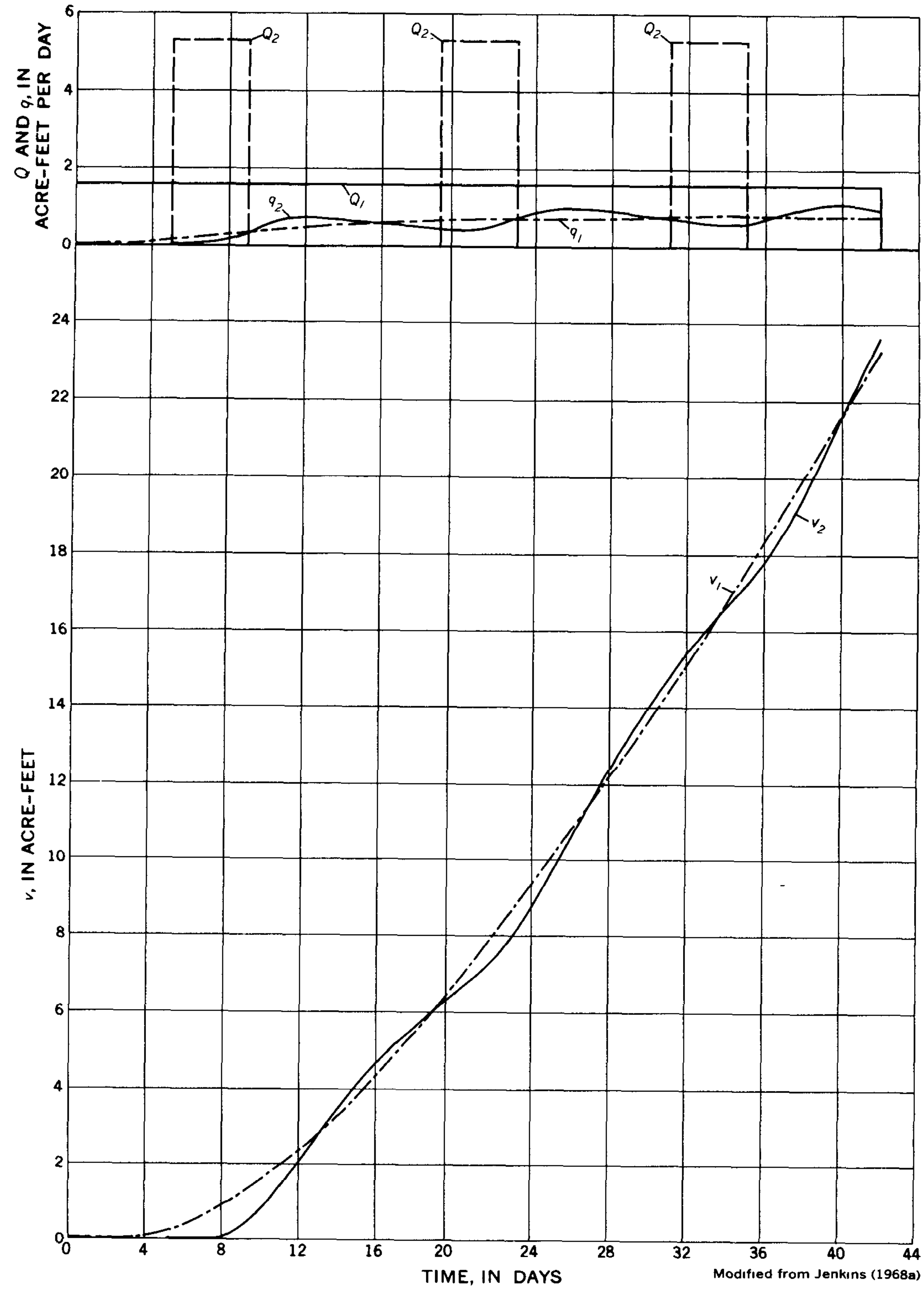

Figure 5.—Curves showing the effects of intermittent and steady pumping on a stream

$$sdf = a^2S/T = \frac{a^2}{T/S} = \frac{(5{,}280 \text{ ft})^2}{134{,}000 \text{ ft}^2/\text{day}} = 209 \text{ days.}$$

Find:

Various pumping patterns possible within the restrictions given.

Part 1

First, test to see if both restrictions apply to any combination of pumping time and rate within the 150-day period. Try ending pumping the last day of the season, beginning pumping at a time and rate such that pumping 150 acre-ft will result in a depletion of the stream of 25 acre-ft at the end of pumping.

$$Qt = 150 \text{ acre-ft}, \; v = 25 \text{ acre-ft}; \; \frac{v}{Qt} = 0.167.$$

From curve B (fig. 1)

$$t/sdf = 0.54.$$

Time will be

$$t = (0.54)\ (209 \text{ days})$$
$= 113$ days, or 37 days after beginning of season.

Pumping rate will be

$$Q = \frac{150 \text{ acre-ft}}{113 \text{ days}} = 1.33 \text{ acre-ft/day.}$$

He can pump 16 hours per day, beginning 113 days before the end of the season.

If pumping 150 acre-ft during the 113-day period at the end of the season results in 25 acre-ft of stream depletion, it follows that pumping 150 acre-ft—regardless of rate—in a shorter period at the end of the season will result in less than 25 acre-ft depletion, and the 150 acre-ft limit will apply. It also follows that pumping 150 acre-ft in the earlier periods will result in more than 25 acre-ft of stream depletion, hence the restriction on stream depletion will apply during the first part of the season.

Part 2

Begin pumping 60 days after the beginning of the season. Test reasoning that the restriction on volume pumped applies.

$$Qt = 150 \text{ acre-ft},$$
$$t = 90 \text{ days},$$

$$t/sdf = \frac{90 \text{ days}}{209 \text{ days}} = 0.43.$$

From curve B

$$\frac{v}{Qt} = 0.13.$$

The volume of stream depletion is

$$v = (0.13)\ (150 \text{ acre-ft}) = 19.5 \text{ acre-ft.}$$

The restriction on the volume of stream depletion has not been exceeded; therefore, the restriction on volume pumped does apply, and the allowable pumping rate would be

$$Q = \frac{150 \text{ acre-ft}}{90 \text{ days}} = 1.67 \text{ acre-ft/day}$$

which is the equivalent of pumping at the rate of 2.00 acre-ft/day for 20 hours per day.

Part 3

Begin pumping at the beginning of the season, pump for 73 days. Test reasoning that the restriction on stream depletion applies.

$$t_p/sdf = 73 \text{ days}/209 \text{ days} = 0.35.$$

From figure 3, for

$$t/sdf = 0.35$$

and

$$\frac{t_p + t_i}{sdf} = \frac{150 \text{ days}}{209 \text{ days}} = 0.72,$$

$$\frac{v}{Qsdf} = 0.12.$$

The steady pumping rate is

$$Q = \frac{25 \text{ acre-ft}}{(0.12)(209 \text{ days})} = 1.00 \text{ acre-ft/day,}$$

and the net volume pumped is

$$Qt = (1.00 \text{ acre-ft/day})\ (73 \text{ days}) = 73 \text{ acre-ft.}$$

Therefore, the restriction on volume of stream depletion does apply. He can pump 12 hours per day at a rate of 2.00 acre-ft/day during a 73-day pumping period at the beginning of the season.

Part 4

The irrigator elects to pump 6 hours per day for the first 32 days of the season. What is the highest rate he can pump during the remaining 118 days?

Try assumption that restriction on volume of stream depletion will apply.

$$t_p/sdf=\frac{32\text{ days}}{209\text{ days}}=0.15$$

and

$$\frac{t_p+t_i}{sdf}=\frac{150\text{ days}}{209\text{ days}}=0.72.$$

From figure 3

$$\frac{v_1}{Qsdf}=0.057.$$

The volume of stream depletion during the 32 days is

$$v_1=(0.057)\ (0.5\text{ acre-ft/day})\ (209\text{ days})$$
$$=6.0\text{ acre-ft}.$$

The net volume pumped during this time is

$$Q_1t_1=(0.5\text{ acre-ft/day})\ (32\text{ days})=16\text{ acre-ft}.$$

Subtract v_1 from the allowable volume of stream depletion

$$25\text{ acre-ft}-6\text{ acre-ft}=19\text{ acre-ft}=v_2.$$

If

$$t_2/sdf=\frac{118\text{ days}}{209\text{ days}}=0.56,$$

then from figure 1

$$\frac{v_2}{Q_2t_2}=0.17.$$

The volume pumped during the 118 days is

$$Q_2t_2=(19\text{ acre-ft})/0.17=112\text{ acre-ft}.$$

The values for the two periods total

$$(112+16)\text{ acre-ft}=128\text{ acre-ft},$$

which is less than 150 acre-ft. Therefore the assumption that restriction on volume of stream depletion applies is correct.

$$Q_2=\frac{112\text{ acre-ft}}{118\text{ days}}=0.95\text{ acre-ft/day}.$$

He can pump at the steady rate of 2.00 acre-ft/day for 11.4 hours per day during the last 118 days of the season.

The irrigator elects to pump continuously at the rate of 2.00 acre-ft/day. If he plans to pump until the end of the season, how soon can he start pumping? (See Part 5.) If he plans to start pumping at the beginning of the season, how long can he pump? (See Part 6.) If he plans to start pumping 50 days after the beginning of the season, how long can he pump? (See Part 7.)

Part 5

$$Qt=150\text{ acre-ft},$$

$$t=\frac{150\text{ acre-ft}}{2\text{ acre-ft/day}}=75\text{ days}$$

$$t/sdf=\frac{75\text{ days}}{209\text{ days}}=0.36.$$

From curve B (fig. 1)

$$\frac{v}{Qt}=0.10.$$

The volume of stream depletion is

$$v=15.0\text{ acre-ft}.$$

Therefore the restriction on volume pumped applies, and he can pump continuously at the rate of 2 acre-ft/day, beginning 75 days before the end of the season.

Part 6

Assume that the restriction on stream depletion applies,

$$\frac{v}{Qsdf}=\frac{25\text{ acre-ft}}{(2\text{ acre-ft/day})\ (209\text{ days})}=0.060$$

and

$$\frac{t_p+t_i}{sdf}=\frac{150\text{ days}}{209\text{ days}}=0.72.$$

From figure 3

$$t_p/sdf\approx 0.17$$

$$t_p\approx(0.17)\ (209\text{ days})\approx 35\text{ days}.$$

Therefore the irrigator can begin pumping at the beginning of the season and pump continuously at a rate of 2.00 acre-ft/day for about 35 days.

Part 7

Restriction on volume pumped limits pumping time to

$$\frac{150 \text{ acre-ft}}{2 \text{ acre-ft/day}}=75 \text{ days.}$$

Test to see if depletion restriction would be exceeded by 75 days of pumping beginning 50 days after the beginning of the season.

$$t_p+t_i=(150-50) \text{ days}=100 \text{ days.}$$

If

$$\frac{t_p+t_i}{sdf}=\frac{100 \text{ days}}{209 \text{ days}}=0.48$$

and

$$t_p/sdf=75 \text{ days}/209 \text{ days}=0.36,$$

then from figure 3

$$\frac{v}{Qsdf}=0.72.$$

The volume of stream depletion is

$$v\approx(0.72)(2 \text{ acre-ft/day})\ (209 \text{ days})$$

$$\approx 30 \text{ acre-ft},$$

which exceeds the 25 acre-ft restriction.

Try stopping pumping after 69 days. Use values from table 1 instead of interpolation between curves in figure 3.

$$t_i=(100-69) \text{ days}=31 \text{ days.}$$

If

$$\frac{t_p+t_i}{sdf}=0.48, \text{ then } \frac{v_1}{Qsdf}=0.070,$$

and if

$$\frac{t_i}{sdf}=0.15, \text{ then } \frac{v_2}{Qsdf}=0.003.$$

The net is

$$\frac{v}{Qsdf}=0.067.$$

The volume of steam depletion is

$$v=28 \text{ acre-ft.}$$

Try $t_p=54$ days, $t_i=46$ days.

$$\frac{t_p+t_i}{sdf}=0.48, \quad \frac{v_1}{Qsdf}=0.070,$$

and

$$\frac{t_i}{sdf}=0.22, \quad \frac{v_2}{Qsdf}=0.010.$$

The net is

$$\frac{v}{Qsdf}=0.060.$$

The volume of stream depletion is

$$v=25 \text{ acre-ft.}$$

Therefore, the irrigator can pump continuously at a rate of 2 acre-ft/day during the 54-day period beginning 50 days after the season begins.

Problem III

A well 4,000 feet from the stream is shut down after pumping at a rate of 250 gal/min for 150 days; $T/S=67{,}000 \text{ ft}^2/\text{day}$.

1. What effect did pumping the well have on the stream during the pumping period?
2. What will be the effect during the next 216 days after pumping was stopped?
3. What would the effect have been if pumping had continued during the entire 366 days?

Given:

Q =250 gal/min
t_p =150 days, 366 days
t_i =216 days
a =4,000 feet
T/S=67,000 ft²/day

$$sdf=\frac{(4000 \text{ ft})^2}{67{,}000 \text{ ft}^2/\text{day}}=239 \text{ days.}$$

Find:

q and v for $t_p=150$ days
q and v for $t_p+t_i=366$ days
q and v for $t_p=366$ days

Part 1

$$t_p/sdf=150 \text{ days}/239 \text{ days}=0.63.$$

The rate of pumping in consistent units is

$$Q=\left(\frac{250 \text{ gal}}{\text{min}}\right)\left(1{,}440\frac{\text{min}}{\text{day}}\right)\left(\frac{1 \text{ ft}^3}{7.48 \text{ gal}}\right)\left(\frac{1 \text{ acre-ft}}{43{,}560 \text{ ft}^3}\right)$$

$$=1.1 \text{ acre-ft/day.}$$

When

$$t=t_p,$$

$$t/sdf=0.63.$$

From curve A

$$q/Q=0.37.$$

From curve *B*

$$\frac{v}{Qt}=0.19.$$

At the end of 150 days,

$$q=(1.1 \text{ acre-ft/day})\ (0.37)$$
$$=0.41 \text{ acre-ft/day},$$
$$v=(1.1 \text{ acre-ft/day})\ (150 \text{ days})\ (0.19)$$
$$=31 \text{ acre-ft}.$$

Part 2

When $t_p+t_i=(150+216)$ days$=366$ days,

$$\frac{t_p+t_i}{sdf}=1.53.$$

From figure 2 by interpolation,

$$q/Q=0.11.$$

From figure 3 by interpolation,

$$\frac{v}{Qsdf}=0.33.$$

Thus, 216 days after pumping ceased,

$$q=(0.11)\ (1.1 \text{ acre-ft/day})$$
$$=0.12 \text{ acre-ft/day},$$
$$v=(0.33)\ (1.1 \text{ acre-ft/day})\ (239 \text{ days})$$
$$=87 \text{ acre-ft}.$$

The additional volume of stream depletion during the 216-day period would be

$$(87-31) \text{ acre-ft}=56 \text{ acre-ft}.$$

Part 3

If pumping had continued for the entire 366-day period,

$$\frac{t}{sdf}=1.53,$$

and from table 1, $q/Q=0.568$ and

$$\frac{v}{Qt}=0.366.$$

$$q=(0.568)\ (1.1 \text{ acre-ft/day})$$
$$=0.62 \text{ acre-ft/day},$$
$$v=(0.366)\ (1.1 \text{ acre-ft/day})\ (366 \text{ days})$$
$$=147 \text{ acre-ft}.$$

During the last 216 days the stream depletion would have been

$$v=(147-31) \text{ acre-ft}=116 \text{ acre-ft}.$$

Problem IV

A municipal well is to be drilled in an alluvial aquifer near a stream. Downstream water uses require that depletion of the stream be limited to no more than 5,000 cubic meters during the dry season, which commonly is about 200 days long. The well will be pumped continuously at the rate of 0.03 m^3/sec (cubic meters per second) during the dry season only. Wet season recharge is ample to replenish storage depleted by the pumping in the previous dry season, thus residual effects can be disregarded. $T=30$ cm^2/sec (square centimeters per second), $S=0.20$.

What is the minimum allowable distance between the well and the stream?

Given:

$v=5{,}000 \text{ m}^3$
$Q=0.03 \text{ m}^3/\text{sec}$
$t_p=200 \text{ days}$
$T=30 \text{ cm}^2/\text{sec}$
$S=0.20$
$Qt=(0.03 \text{ m}^3/\text{sec})\ (200 \text{ days})\ (86{,}400 \text{ sec/day})=5.184\times 10^5 \text{m}^3$

$$\frac{v}{Qt}=5{,}000 \text{ m}^3/5.184\times 10^5 \text{ m}^3=0.01.$$

Find: *a*

From curve *B*

$$t/sdf=0.12=\frac{tT}{a^2S},$$

$$0.12=\frac{(200 \text{ days})\ (86{,}400 \text{ sec/day})\ (30 \text{ cm}^2/\text{sec})}{a^2(0.20)},$$

$$a^2=\frac{(200)\ (86{,}400)\ (30) \text{ cm}^2}{(0.12)\ (0.20)}=2.16\times 10^{10} \text{ cm}^2,$$

$$a=1.47\times 10^5 \text{ cm}=1{,}470 \text{ meters}.$$

Problem V

A water company wants to install a well near a stream and pump it 90 days during the summer to supplement reservoir supplies. Downstream residents have protested that the well might dry up the stream. Natural streamflow at the lower end of the reach that would be affected by pumping is not expected to go below 2.0 ft³/sec in most years, and the downstream users have agreed that the well can be installed if depletion of the stream is limited to a maximum of 1.5 ft³/sec. The well would be 500 feet from the the stream and would pump 1,000 gpm. T=50,000 gpd/ft, and S =0.20.

1. Will the rate of stream depletion exceed 1.5 ft³/sec during the first season or any following season?
2. If so, when will the rate of stream depletion exceed 1.5 ft³/sec?
3. At what rate could the well be pumped in order not to exceed 1.5 ft³/sec of stream depletion?

Given:

q max allowable=1.5 ft³/sec
a=500 feet
T=50,000 gal/day-ft
S=0.20
Q=1,000 gal/min

$$sdf=\frac{(500\text{ ft})^2(0.20)(7.48\text{ gal/ft}^3)}{50{,}000\text{ gal/day-ft}}=7.5\text{ days}$$

Find:

q max
t for q=1.5 ft³/sec
Q for q=1.5 ft³/sec

Part 1

$$t_p=90\text{ days.}$$

$$t_p/sdf=12.$$

From figure 1,

$$1-q/Q=0.155.$$

Therefore

$$q/Q=0.845,$$

$$q=\frac{(0.845)(1{,}000\text{ gal/min})(1{,}440\text{ min/day})}{7.48\text{ gal/ft}^3}$$

$$=1.63\times10^5\text{ ft}^3\text{/day}$$

$$=1.88\text{ ft}^3\text{/sec.}$$

Therefore by the end of the first pumping period, the rate of stream depletion would have exceeded the allowable depletion of 1.5 ft³/sec.

Part 2

$$q=1.5\text{ ft}^3\text{/sec}=(1.5\text{ ft}^3\text{/sec})\ (86{,}400\text{ sec/day})$$

$$=1.30\times10^5\text{ ft}^3\text{/day}$$

$$Q=1{,}000\text{ gal/min}$$

$$=\frac{(1{,}000\text{ gal/min})(1{,}440\text{ min day})}{7.48\text{ gal/ft}^3}$$

$$=1.93\times10^5\text{ ft}^3\text{/day}$$

$$q/Q=1.30\times10^5/1.93\times10^5=0.67$$

$$1-q/Q=1.00-0.67=0.33.$$

From figure 1, curve $1-q/Q$

$$t/sdf=2.7,$$

$$t=(2.7)\ (7.5)=20\text{ days.}$$

Therefore, the rate of stream depletion will exceed 1.5 ft³/sec after 20 days pumping at 1,000 gal/min.

Part 3

From "Part 1," q/Q=0.845.

$$Q=q/0.845$$

$$=(1.30\times10^5\text{ ft}^3\text{/day})/0.845$$

$$=1.54\times10^5\text{ ft}^3\text{/day}$$

$$=800\text{ gal/min.}$$

Therefore, if pumping were reduced to 800 gal/min, the rate of stream depletion would not exceed 1.5 ft³/sec during the first 90-day period of pumping.

However, the residual effects of this pumping would carry over through the next pumping period.

The residual effect of the first pumping period on rate of stream depletion at the end of the second period, assuming no pumping during the second period, is as follows:

$$t_p+t_i=90\text{ days}+365\text{ days}=455\text{ days.}$$

$$\frac{t_p+t_i}{sdf}=61,\ t_i/sdf=49.$$

From figure 1,

$$(1-q/Q)_{p+i}=0.073,$$

$$(1-q/Q)_i=0.081,$$

and

$$q/Q=0.008.$$

Thus the rate of depletion is

$$q=(0.008)\ (1.54\times10^5\ \text{ft}^3/\text{day})$$

$$=1{,}230\ \text{ft}^3/\text{day}$$

$$=0.014\ \text{ft}^3/\text{sec}.$$

The effects are very slight. Pumping 800 gal/min during the second pumping period would exceed the allowable stream depletion rate by only 0.014 ft^3/sec. Reduction of the pumping rate to about 750 gal/min would keep rate of stream depletion below 1.5 ft^3/sec during several successive pumping seasons.

Mathematical Bases for Curves and Tables

The literature concerning the effect of a pumping well on a nearby stream contains several equations and charts that, although superficially greatly different, yield identical results. The basic curves and table (Curves *A* and *B*, and table 1) of this report can be derived from any of the published expressions. A cursory review of some of the pertinent equations may be useful to those interested in the mathematics.

Definitions

The notation that has been used in the literature is even more diverse than the published equations; consequently, definitions of only selected terms are given below. Complete definitions of all terms used are in the indicated references.

erf x=the error function of x

$$=\frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2}dt=1-\text{erfc}\,x$$

erfc x=the complementary error function of x

$$=\frac{2}{\sqrt{\pi}}\int_x^\infty e^{-t^2}dt$$

i^2erfc x=the second repeated integral of the error function.

The line source integral (Maasland and Bittinger, 1963, p. 84)

$$=\sqrt{\pi}\int_{x/\sqrt{4h^2t}}^{\infty}\frac{e^{-u^2}du}{u^2}$$

In the notation used in the main body of this report,

$$x/\sqrt{4h^2t}=\sqrt{\frac{sdf}{4t}}$$

Definitions and tabular values of erf x ,erfc x, and i^2erfc x are shown by Gautschi (1964, p. 297, 310–311, 316–317). Tabular values of the line source integral are shown by Maasland and Bittinger (1963, p. 84) and by Glover (1964, p. 45–53).

Mathematical base for curve A

Curve *A* and its coordinates in table 1 can be computed from Theis (1941), Conover (1954), and Theis and Conover (1963)

$$P=\frac{2}{\pi}\int_0^{\pi/2}e^{-k\sec^2 u}du \qquad (1)$$

from Glover and Balmer (1954)

$$q/Q=1-P(x_1/\sqrt{4\alpha t}) \qquad (2)$$

from Glover (1960)

$$q_1/Q=1-\frac{2}{\sqrt{\pi}}\int_0^{x_1/\sqrt{4\alpha t}}e^{-u^2}du \qquad (3)$$

and from Hantush (1964, 1965)

$$Q_r=Q\text{erfc}\ (U) \qquad (4)$$

Theis transformed his basic integral into equation 1 because the basic integral is laborious to evaluate, but in the form of equation 1, is amenable to either numerical or graphical solution. Equations 2, 3, and 4 are identical, and in the notation used in this paper are

$$q/Q=\text{erfc}\left(\sqrt{\frac{sdf}{4t}}\right)=1-\text{erf}\left(\sqrt{\frac{sdf}{4t}}\right). \qquad (5)$$

Mathematical base for curve B

Curve B and its coordinates in table 1 can be computed either by integration of curve A or of the equations that are the base of curve A. Analytical integration of equations 2 and 3 is shown by Glover (1960) as

$$\int_0^t \frac{q_r}{Q}\,dt = 1 - \frac{2}{\sqrt{\pi}}\int_0^{x_1/\sqrt{4\alpha t}} e^{-u^2}du - \frac{2}{\pi}\left(\frac{x_1^2}{4\alpha t}\right)\sqrt{\pi}\int_{x_1/\sqrt{4\alpha t}}^{\infty} \frac{e^{-u^2}}{u^2}\,du \quad (6)$$

and equation 4 is integrated by Hantush (1964, 1965)

$$v_r = \int_0^{t_0} Q_r\,dt = 4Qt_0 i^2 \operatorname{erfc}(U_0) \quad (7)$$

In the notation used in this paper, equation 6 is

$$\frac{v}{Qt} = 1 - \operatorname{erf}\left(\sqrt{\frac{sdf}{4t}}\right) - \frac{2}{\pi}\left(\frac{sdf}{4t}\right)\sqrt{\pi}\int_{\sqrt{\frac{sdf}{4t}}}^{\infty} \frac{e^{-u^2}}{u^2}\,du \quad (8)$$

and equation 7 is

$$\frac{v}{Qt} = 4i^2 \operatorname{erfc}\left(\sqrt{\frac{sdf}{4t}}\right). \quad (9)$$

Equations 8 and 9 both can be expressed in terms extensively tabulated in Gautschi (1964, p. 310–311) as

$$\frac{v}{Qt} = \left(\frac{sdf}{2t}+1\right)\operatorname{erfc}\left(\sqrt{\frac{sdf}{4t}}\right) - \left(\sqrt{\frac{sdf}{4t}}\right)\frac{2}{\sqrt{\pi}}\exp\left(-\frac{sdf}{4t}\right) \quad (10)$$

Before discovering equations 6 and 7, the writer integrated curve A both numerically and graphically. The results were identical, within the limitations of the methods, to those obtained from equation 10.

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Appendix G

United States Department of the Interior

U.S. GEOLOGICAL SURVEY
Nebraska Water Science Center
5231 South 19 Street
Lincoln, NE 68512-1271

November 2, 2005

Ann S. Bleed, Acting Director
Nebraska Department of Natural Resources
P.O. Box 94676
Lincoln, NE 68509-4676

Dear Ann:

The U.S. Geological Survey Nebraska Water Science Center (NWSC) acknowledges the State of Nebraska Department of Natural Resources (NDNR) request for review of "Stream Depletion Line Calculations for Determination of Fully Appropriated Basins for the State of Nebraska". We were pleased to perform this task for NDNR. I assigned this review to Richard Luckey, Gregory Steele, and Steve Peterson, who are NWSC hydrologists experienced with the development of numerical models that describe ground water/surface water interactions.

The NWSC reviewers found the document to be technically sound, but have made suggestions to improve the final product. Copies of the reviewers notes and list of their recommendations are enclosed. Please feel free to contact me directly at (402) 328-4110 if we can be of further assistance.

Sincerely,

Robert B. Swanson
Director

Enclosure